In compliance with the
Canadian Privacy Legislation
some supporting forms
may have been removed from
this dissertation.

While these forms may be included
in the document page count,
their removal does not represent
any loss of content from the dissertation.

University of Alberta

DEVELOPMENT OF LOW PROTEIN DIETS FOR SOWS: EFFECT ON PERFORMANCE AND ENERGY METABOLISM

by

DEIDRA JANINE MCMILLAN

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Animal Science

Department of Agricultural, Food and Nutritional Science

Edmonton, Alberta

Fall, 2003

National Library of Canada
Acquisitions and Bibliographic Services
395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale du Canada
Acquisisitons et services bibliographiques
395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 0-612-87833-3
Our file Notre référence
ISBN: 0-612-87833-3

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou aturement reproduits sans son autorisation.

Canada

University of Alberta

Library Release Form

Name of Author: Deidra Janine McMillan

Title of Thesis: Development of Low Protein Diets for Sows: Effect on Performance and Energy Metabolism

Degree: Master of Science

Year this Degree Granted: 2003

Permission is hereby granted to the University of Alberta Library to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves all other publication and other rights in association with the copyright in the thesis, and except as herein before provided, neither the thesis nor any substantial portion thereof may be printed or otherwise reproduced in any material form whatever without the author's prior written permission.

Sept 18, 2003

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Development of Low Protein Diets for Sows: Effect on Performance and Energy Metabolism submitted by Deidra Janine McMillan in partial fulfillment of the requirements for the degree of Master of Science in Animal Science.

Dr. R.O. Ball

Dr. W.M. Sauer

Dr. G. W. Foxcroft

Dr. S. Möhn

Dr. V. E. Baracos

Sept 18, 2003

ABSTRACT

Eighty 2nd parity sows received either conventional diets (HP) for gestation and lactation containing 16.3% CP and 21.1% CP or rations containing 13.5% CP and 18.2 % CP supplemented with lysine and threonine (LP). All diets met or exceeded the current requirements (NRC, 1998) for all nutrients. Sows were paired according to initial body weight and backfat, and were maintained on their allotted dietary treatment for two consecutive parities. Sow performance characteristics including weight and backfat changes, number of piglets born and weaned, piglet growth rate, milk production and composition and reproductive adequacy were evaluated. Metabolic criteria including diet digestibility, urinary nitrogen excretion and energy expenditure were measured in a subset of sows (n = 22), and plasma amino acids were determined in 6 sows per treatment (n = 12). Performance was maintained by the low protein diet during gestation, but was more variable during lactation.

ACKNOWLEDGEMENTS

I would sincerely like to thank my supervisor, Dr. Ron O. Ball for his encouragement and support throughout my studies. I would especially like to thank Dr. Sönke Möhn, for thinking up this long, complex, and utterly amazing project to foist off on some poor unsuspecting Masters student. I have learned more than I ever imagined about sow production, nutrition and metabolism, over the course of this degree.

I sincerely appreciate the assistance of my fellow lab mates, Robyn Harte, Semone Myrie, Kate Shoveller, Desmond Pink, Raja Elango, Kristine Urschel, Dana Wilkinson, and would especially like to thank Jacob Atakora for helping me with so many weigh-suckle-weigh measurements. Twenty-two sows, four measurements, eight hours each. You do the math.

A special thank you to my husband, Bob McMillan, who managed to live as a bachelor in another city for nearly three years while his wife went off to become more "edumacated". Thanks for believing in me.

I would like to acknowledge the assistance of all the staff at the University of Alberta's Swine Research and Technology Centre, in making this project run so smoothly, and the staff at the Metabolic Unit, who graciously put up with sows running through their hallways several times a week. Special thanks to Charlene and Brenda for catheterizing all those sow ears, over and over again!

Of course, I must acknowledge my parents, who raised me to believe that I could do anything, and supported me in whatever I chose. And finally, I must thank Simon Goodwin, my employer before I decided to come back to University to get my Masters degree, who believed in me enough to help me get here.

The sows are the heroes of this degree. I can never forget that they are the true reason this thesis exists.

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 LITERATURE REVIEW: Considerations for the Implementation of Low Protein, Amino Acid Supplemented Diets to Sow Production 3

2.1 IMPLICATIONS OF OVERFEEDING PROTEIN TO SWINE 3

2.2 APPLICATION OF THE IDEAL PROTEIN CONCEPT TO SOWS 4

2.3 OVERVIEW OF AMINO ACID REQUIREMENTS FOR SOWS 7

2.3.1 Current Knowledge of Amino Acid Requirements 9

2.3.2 Amino Acid Requirements During Gestation 11

2.3.3 Amino Acid Requirements For Lactation 14

2.3.4 The Influence of Protein: Energy Interactions on Sow Amino Acid Requirements 18

2.3.5 Factors Controlling Feed Intake 19

2.3.6 Relationship Between Feeding Frequency and Utilization of Amino Acids in Supplemented Diets 21

2.4 PHYSIOLOGICAL EFFECTS OF FEEDING LOW PROTEIN, AMINO ACID SUPPLEMENTED DIETS 23

2.4.1 Digestibility of Low Protein, Amino Acid Supplemented Diets 23

2.4.2 Intermediary Metabolism of Nitrogen in Amino Acid Supplemented, Low Protein Diets 24

2.4.3 Intermediary Metabolism: Energy 26

2.4.4 Changes In Body Composition 29

2.5 APPLICATION OF LOW PROTEIN DIETS 31

2.5.1 Low Protein Amino Acid Supplemented Diets for Sows 31

2.5.2 Limitations to Using Low Protein, Amino Acid Supplemented

Diets 34

2.6 SUMMARY 35

2.7 LITERATURE CITED 36

3.0 HYPOTHESIS & OBJECTIVES 45

3.1 HYPOTHESES 45

3.2 OBJECTIVES 46

4.0 INTRODUCTION 48

4.1 MATERIALS AND METHODS 48

4.1.1 Experimental Design 49

4.1.1.1 Sow Selection 49

4.1.1.2 Housing and Management 50

4.1.2 Diets and Feeding 50

4.1.2.1 Diet Composition 50

4.1.2.2 Feeding Regimen 57

4.1.3 Production Measurements 58

4.1.3.1 Weighing and Measurement of Backfat Depth 58

4.1.3.2 Estrus Detection and Measurement of Reproductive Adequacy 58

4.1.3.3 Litter Characteristics 59

4.1.4 Intensive Measurements 60

4.1.4.1 Respiration Procedures 60

4.1.4.2 Milk Production and Composition 64

4.1.4.3 Determination of Nitrogen Excretion 65

4.1.4.4 Determination of Diet Digestibility 65

4.1.4.5 Determination of Body Water Content: Deuterium Oxide 66

4.1.5 Chemical Analyses 67
4.1.6 Statistical Analyses 72
5.0 RESULTS 75
5.1 Animal Performance 75
5.1.1 Performance of All Sows 75
5.1.2 Characteristics of Piglets Nursing All Sows 84
5.1.3 Feed Intake of All Sows 86
5.1.4 Performance of Sows Allocated to Intensive Measurements 88
5.1.5 Characteristics of Piglets Nursing Intensive Sows 92
5.1.6 Feed Intake of Intensive Sows 93
5.2 Milk Yield, Composition, and Amino Acids 98
5.2.1 Milk Yield 98
5.2.2 Milk Composition 104
5.2.3 Milk Amino Acids 110
5.3 Diet Composition and Amino Acid Balance 111
5.3.1 Gestation Diets and Intake 111
5.3.2 Lactation Diets and Intake 115
5.3.3 Amino Acid Intake of Intensive Sows 119
5.4 Apparent Fecal Digestibility of Nutrients 121
5.5 Nitrogen Excretion and Plasma Amino Acids 124
5.5.1 Urinary Nitrogen Excretion 124
5.5.2 Plasma Amino Acid Profiles 128
5.6 Energy Expenditure 132
5.7 Body Composition by Deuterium Oxide 140
5.8 Economic Analysis 140
6.0 DISCUSSION 142

6.1 Effect of Low Protein, Amino Acid Supplemented Diets on Animal Performance 142
6.1.1 Gestation Performance 143
6.1.2 Lactation Performance 150
6.1.3 Summary of Changes in Sow Weight and Backfat and Carry-over Effects 158
6.1.4 Piglet Characteristics, Milk Production and Composition 160
6.1.4.1 Piglet Characteristics and Milk Production 160
6.1.4.2 Milk Composition 166
6.1.4.3 Milk Amino Acid Concentration 169
6.2 Effect of Low Protein, Amino Acid Supplemented Diets on Sow Metabolism 170
6.2.1 Nitrogen Excretion 170
6.2.2 Energy Expenditure 175
6.2.2.1 Overall Energy Expenditure 176
6.2.2.2 Gestation Energy Expenditure 179
6.2.2.3 Lactation Energy Expenditure 181
6.3 Economic Analysis 183
7.0 SUMMARY AND CONCLUSIONS 185
7.1 Summary of Discussion 185
7.2 Conclusions 187
8.0 FUTURE DIRECTIONS 193
9.0 LITERATURE CITED 196

LIST OF TABLES

Table 2.1.1	Ideal ratios of indispensable amino acids to lysine for various metabolic functions and specific ratios for sows	7
Table 2.1.2	Current knowledge on the amino acid requirements of sows: number of peer-refereed publications, and most recent research dates	8
Table 4.1.1	Gestation diet composition	52
Table 4.1.2	Calculated true ileal digestible amino content of the gestation diets	53
Table 4.1.3	Lactation diet composition	55
Table 4.1.4	Calculated true ileal digestible amino acid content of the lactation diets	56
Table 5.1.1	Effect of diet and parity on sow weight and backfat, and on reproductive adequacy	77
Table 5.1.2	Effect of diet and parity on mean changes in individual sow weight and backfat	80
Table 5.1.3	Effect of diet and parity on daily live weight changes	81
Table 5.1.4	Interaction between diet and parity on gestation weight gain from breeding to early pregnancy	83
Table 5.1.5	Effect of diet and parity on litter weights at birth and weaning and nursed piglet weights and growth rate	85
Table 5.1.6	Effect of diet and parity on feed and nutrient intake of gestating and lactating sows	87
Table 5.1.7	Effect of diet and parity on weight and backfat of intensive sows, and on their wean to estrus interval	89
Table 5.1.8	Effect of diet and parity on mean changes in individual intensive sow weight and backfat	90
Table 5.1.9	Effect of diet and parity on daily live weight changes of intensive sows	91
Table 5.1.10	Effect of diet and parity on litter weights at birth and weaning, and weights and growth rate of piglets nursing intensive sows	93
Table 5.1.11	Effect of diet and parity on feed and nutrient intake of gestating and lactating intensive sows	94
Table 5.2.1	Effect of diet, stage of lactation and parity on milk yield	99
Table 5.2.2	Trends for interaction between stage and parity on milk yield	100

Table 5.2.3	Pearson correlation matrix for milk yield and composition, using a variety of sow related factors	101
Table 5.2.4	Stepwise multiple regression to determine the factors affecting milk yield (kg/day)	104
Table 5.2.5	Effect of diet, stage of lactation, and parity on the composition of sow's milk	105
Table 5.2.6	Stepwise multiple regression of factors affecting milk crude protein	107
Table 5.2.7	Stepwise multiple regression of factors affecting milk dry matter content (%)	108
Table 5.2.8	Stepwise multiple regression of factors affecting milk fat (%)	109
Table 5.2.9	Stepwise multiple regression of factors affecting milk gross energy content (kcal/kg)	109
Table 5.2.10	Amino acid content of milk protein (g AA/ 16 g N)	110
Table 5.3.1	Total amino acid content of the gestation diets and daily intake of amino acids during the second parity	112
Table 5.3.2	Total amino acid content of the gestation diets and daily intake of amino acids during the third parity	113
Table 5.3.3	Ratio of total amino acids to lysine in the gestation diets as compared to NRC (1998)	114
Table 5.3.4	Total amino acid content of the lactation diets and daily intake of amino acids during the second parity	116
Table 5.3.5	Total amino acid content of the lactation diets and daily intake of amino acids during the third parity	117
Table 5.3.6	Ratio of total amino acids to lysine in the lactation diets as compared to NRC (1998)	118
Table 5.3.7	Amino acid content of the lactation diets and daily intake of amino acids during the second parity: Intensive sows	120
Table 5.3.8	Amino acid content of the lactation diets and daily intake of amino acids during the third parity: Intensive sows	120
Table 5.4.1	Effect of diet, stage and parity on the apparent digestibility coefficients of nutrients during gestation	121
Table 5.4.2	Interaction between diet and parity on apparent digestibility coefficients of nutrients in the gestation diets	122

Table 5.4.3	Effect of diet, stage and parity on apparent digestibility coefficients of nutrients during lactation	123
Table 5.5.1	Effect of diet, physiological state, stage of gestation or lactation and parity on excretion of creatinine, nitrogen and their ratio in urine spot samples	125
Table 5.5.2	Interaction among parity, physiological state (gestation or lactation) and stage (early or late) on nitrogen: creatinine ratio in urine	126
Table 5.5.3	Effect of diet and physiological state on plasma amino acids (μM/L)	129
Table 5.5.4	Interaction between diet and physiological state on some plasma amino acids (μM/L)	131
Table 5.6.1	Effect of diet, physiological state, stage and parity on gas exchange, heat production and respiratory quotient of sows	133
Table 5.6.2	Interaction between physiological state and parity on overall sow gas exchange and heat production	134
Table 5.6.3	Interaction between physiological state and stage on daily heat production per unit of metabolic body weight	134
Table 5.6.4	Effect of diet, stage and parity on the gas exchange, heat production and respiratory quotient of sows during gestation	136
Table 5.6.5	Interaction between diet and parity on carbon dioxide production in gestating sows	136
Table 5.6.6	Effect of diet, stage and parity on gas exchange, heat production and respiratory quotient of sows during lactation	137
Table 5.6.7	Effect of diet, stage and parity on gas exchange and heat production of the sow and her litter during lactation	139
Table 5.7.1	Average feed cost for the experimental period	140
Table 5.7.2	Feed cost, piglet revenue and margin over feed cost of average weaned piglets for variable and constant amino acid pricing	141

LIST OF FIGURES

Figure 4.1.1	Diagram of respiration system	63
Figure 5.1.1	Sow body weight throughout the complete experiment	78
Figure 5.1.2	Sow backfat changes throughout the experimental period	78
Figure 5.1.3	Effect of dietary treatment on the daily feed intake pattern of intensive sows throughout lactation	96
Figure 5.1.4	Effect of parity on the daily feed intake pattern of intensive sows throughout lactation	97
Figure 5.5.1	Interaction among physiological state, parity and stage on urinary nitrogen: creatinine ratio	126
Figure 5.5.2	Interaction among diet, parity, physiological state, and stage on the nitrogen: creatinine ratio	128

1.0 INTRODUCTION

Nutritionists formulate swine diets according to their best knowledge of the amino acid requirements of the animal. This task is complicated, however, by the rapid improvements in animal productivity, caused by continual genetic selection for faster growth rates and productive capacity. Therefore, the main focus of diet formulation has been to obtain maximal performance with minimum economic input, without closely matching diet nutrient supply with animal requirement. Generally, in order to ensure that the requirement for the first limiting amino acid, lysine, is met, swine diets contain excesses of all other amino acids. However, as public scrutiny of the industry increases, the environmental consequences of feeding such excess protein diets must taken into consideration.

Surplus amino acids consumed by the pig will be degraded, and the nitrogen excreted in the urine as urea (Wilkinson et al, 1984). Manure from swine operations is often used as fertilizer, and the nitrogen in manure will be deposited into the soil (Misselbrook et al, 1998). High concentrations of deposited nitrogen can build up in the environment, leading to a myriad of problems. However, by reducing dietary crude protein intake and supplementing with indispensable amino acids that may be limiting to animal performance, the nitrogen excreted in pig manure, and specifically the urine, can be drastically reduced. Until recently, crystalline amino acids, excepting lysine, were too expensive to use constantly in least-cost diet formulations. However, the commercial availability of synthetic amino acids is increasing and lysine, methionine and threonine are now readily available at commercially competitive prices. This has enabled nutritionists to utilize free amino acids more often in the formulation of diets. However, this practice has not been widely adopted in North America, to date.

There is a relatively limited body of research describing the efficacy of low protein, amino acid supplemented diets to support pig performance and growth. Much of the information available focuses on growing and finishing pigs with very little on reproducing

sows. Sows comprise only a small portion of the Canadian swine population, but are responsible for nearly 20% of the nitrogen excreted each year (Mathison et al, 1999), and thus are ideal candidates for the implementation of these diets. The available literature clearly demonstrates the efficacy of low protein, amino acid supplemented diets in reducing nitrogen excretion by growing pigs (Jongbloed and Lenis, 1992; Sutton et al, 1999; Renaudeau et al, 2001). However, performance of growing and finishing pigs fed these diets has been highly variable. Furthermore, results from studies on growing animals are not useful in determining performance of sows receiving low protein, amino acid supplemented diets. The sow literature focuses mainly on lactation performance, with little examination of low protein diets during gestation. Additionally, little information is available on the metabolic consequences of feeding such diets to sows. Clearly, further work in this area is needed, if low protein diets are to be commercially accepted on a widespread basis. Therefore, in the interest of expanding the information base and encouraging the feed industry to adopt environmentally sound feed formulation practices, there is a need to examine a wide variety of productive and metabolic parameters, over a period of time, to obtain a relatively comprehensive picture of how feeding low protein, amino acid supplemented diets to sows affects performance and metabolism.

2.0 LITERATURE REVIEW: Considerations for the Implementation of Low Protein, Amino Acid Supplemented Diets to Sow Production

2.1 Implications of Overfeeding Protein To Swine

Swine diets are typically formulated to contain sufficient crude protein to meet the requirement of the first limiting amino acid, lysine. When feedstuffs are combined to meet the animal's lysine requirement, the concentrations of the other indispensable amino acids are generally in excess of their recommended levels. These excess amino acids are not retained by the body, but are degraded, and their nitrogen excreted in the urine. Sows excrete approximately 76% of the nitrogen they consume (Lenis, 1989). Although sows comprise a small portion of the Canadian swine population (10%), they are responsible for 20% of the nitrogen excreted from swine production each year (Mathison et al, 1999).

The concentration of nitrogen excreted in the feces is generally not affected by dietary protein (Kerr and Easter, 1995), because it is a function of diet characteristics and digestive capacity of the pig. The nitrogen excreted in urine, however, results from basal nitrogen catabolism and from the degradation of excess amino acids, absorbed from the small intestine, that cannot be utilized by the pig for protein synthesis (Lenis, 1989). Nearly 70% of the excreted nitrogen is in the form of urinary urea, which rapidly degrades to produce ammonia (van der Peet-Schwering and den Hartog, 2000). Most of the slurry created by swine operations is spread on the land as fertilizer (Misselbrook et al, 1998) and in areas with dense swine populations, this manure can cause serious environmental damage (Honeyman, 1993). Slurry application can lead to pollution of the soil, water and air through nitrate leaching, ammonia volatilization and emission of greenhouse gases such as methane and nitrous oxide (Misselbrook et al, 1998). Because nitrogen is highly water soluble (Honeyman, 1993), applications of manure on the soil can result in leaching of nitrates into fresh water sources

(Lenis, 1989). Ammonia and other volatile compounds (e.g. sulphides, phenols, indoles, volatile fatty acids) are emitted from manure shortly after excretion, causing offensive odors (Sutton et al, 1999). Nearly 90 % of the ammonia emissions in Europe are a result of animal husbandry (Jongbloed and Lenis, 1992; Lenis and Jongbloed, 1999).

Aside from environmental consequences, volatilization of urea nitrogen from manure can also create health concerns. Continuous exposure to low concentrations of manure gases (Jamroz and Kubizna, 2001) or high concentrations of ammonia in the pig barn (Drummond et al, 1980) cause reduced performance. Furthermore, high concentrations of ammonia (Drummond et al, 1980; Jamroz and Kubizna, 2001) or prolonged exposure to low concentrations cause irritation of the respiratory tract of the pig and farm workers (Kirkhorn and Garry, 2000).

The excretion of nitrogen in the urine and subsequent release of ammonia and other gases, as a result of swine production can, however, be drastically reduced. Reduction can be achieved by commercially formulating diets to more closely match the ideal protein pattern for that particular stage of swine production, and through the inclusion of synthetic amino acids, to meet the requirements for the first three or four limiting amino acids. It is important that such procedures be implemented into practice, because both public pressure and government legislation will likely increase in the near future, forcing the swine industry to make changes to become more environmentally friendly, and better protect the health of those who work in the industry.

2.2 Application of the Ideal Protein Concept to Sows

To reduce excess crude protein in the diet and more closely meet the requirements of the pig, diets can be formulated based on an optimal ratio or "ideal protein". An ideal protein provides a balance of amino acids in exactly the proportions in which they are required by the

animal (Fuller, Beckett and Wang, 1989). This balance can be achieved either by combining various intact protein sources, or through the use of synthetic amino acids, and cannot be improved by any addition or substitution of amino acids (Fuller, Beckett and Wang, 1989). For growing pigs, a true ideal amino acid profile optimizes the utilization of dietary nitrogen for growth, regardless of feed intake (Gomez et al, 2002). The first published ideal ratios for swine appeared in the Agricultural Research Council's "The nutrient requirements of pigs", just over twenty years ago (ARC, 1981). These early attempts to characterize amino acid requirements in this manner were provided in terms of total amino acids, which does not account for differences in digestibility between feedstuffs and between amino acids within a feedstuff. Currently the ideal ratio is stated in terms of true ileal digestible amino acids, which is more physiologically accurate, because it attempts to account for those differences (Tuitoek et al, 1997a; Han et al, 2001). Unlike ARC (1981), the NRC (1998) provides ideal ratios in terms of true ileal digestible amino acids. Ideal ratios provided by both ARC (1981) and NRC (1998), however, are stated according to the ratio of each indispensable amino acid to lysine. Lysine was chosen as the base amino acid, because it is first limiting in most swine diets, is utilized mainly for protein synthesis, and is relatively easy to quantify (Koch, 1996).

The amino acid profile needed for each body function is unique (Black and Davies, 1991; Edwards and Campbell, 1993) and differs greatly between maintenance, protein accretion and milk synthesis (Table 2.1.1). The animal's total amino acid requirement will depend on the relative contributions of these body functions to it's overall needs (Fuller et al, 1989). Determining the ideal ratio required by growing swine is considered to be relatively simple, because it represents the amino acid balance required for maintenance and muscle protein accretion (Tuitoek et al, 1997a). The profiles proposed by researchers for growing swine, however, have varied considerably, mainly indicative of differing protein accretion rates (Fuller et al, 1987). For sows, the situation is further complicated by the growth of conceptus products in gravid swine, milk production during lactation, and changes in weight and metabolism of the

sow. The optimal profile suggested for lactating sows is similar to that of milk protein (Table 2.1.1), however this simple approach probably does not accurately reflect the metabolic needs of the animal.

The ideal amino acid ratios for sows, as proposed by NRC (1998), are fixed for all situations. However, the profile of amino acids required during lactation or gestation is not static. During lactation, the ideal amino acid pattern must change, depending on the balance between body maintenance, tissue mobilization, milk production and mammary gland growth (Kim et al, 2001). Therefore, the optimal ratio of amino acids required in the diet will vary greatly, depending on the metabolic status of the sow. As the amount of maternal tissue mobilization decreases, the order of limiting amino acids within a diet will change. For example, valine becomes more limiting than threonine in a corn-soybean meal diet when tissue mobilization decreases towards zero (Kim et al, 2001). In addition, as animals mature, maintenance accounts for an increasingly larger proportion of the total requirement. The requirements for methionine plus cystine, and threonine for tissue maintenance are higher than that for lysine, while the needs of these amino acids for protein accretion are relatively less than lysine (Koch, 1996) (Table 2.1.1). Therefore, the profile of amino acids required by young sows, which are still growing, should be greatly different from that required by mature sows, at the same physiological state (i.e. gestation and lactation).

Evidence suggests that there is also an optimal ratio of indispensable to dispensable amino acids (Fuller et al, 1987). Diets must therefore provide the optimal level of dispensable amino acids as well as the optimal ratio of indispensable amino acids to lysine. The ratio proposed for growing pigs is 45% indispensable to 55% dispensable (Koch, 1996). If dispensable amino acids are provided below this optimal ratio, indispensable amino acids must be catabolized to provide nitrogen and carbon skeletons for synthesis of dispensable amino acids, possibly creating an imbalance of indispensable amino acids. This may be especially important when utilizing low protein diets (Lenis and Jongbloed, 1999), because extensive

decreases in crude protein content will also reduce the amount of nitrogen available for dispensable amino acid synthesis.

Table 2.1.1 Ideal ratios of indispensable amino acids to lysine for various metabolic functions and specific ratios for sows

Amino Acid	Maintenance[a]	Protein Accretion [a]	Milk Synthesis [a]	Body Tissue[a]	Gestation [b]	Lactation [c]
Arginine	-200	48	66	105	8	56
Histidine	32	32	40	45	32	41
Isoleucine	75	54	55	50	53	56
Leucine	70	102	115	109	96	114
Lysine	**100**	**100**	**100**	**100**	**100**	**100**
Methionine	28	27	26	27	28	27
Cystine	95	28	19	18	38	23
Phenylalanine	50	60	55	60	58	54
Tyrosine	71	33	57	43	38	58
Threonine	151	60	58	58	74	62
Tryptophan	26	18	18	10	20	18
Valine	67	68	85	69	68	85

a) ideal ratios as expressed in NRC (1998)
b) ideal ratio of true ileal digestible amino acids for a 125 kg sow carrying 11 piglets, and gaining 55 kg during gestation (NRC, 1998)
c) ideal ratio of true ileal digestible amino acids for a 175 kg sow nursing piglets gaining 200 g/d and losing 0 kg body weight during lactation (NRC, 1998)

2.3 Overview of Amino Acid Requirements of Sows

To successfully implement low protein, amino acid supplemented sow diets as a method of reducing the environmental impact of swine production, we must have a firm understanding of the amino acid requirements of sows throughout their productive cycle. To properly formulate low protein diets, the order of limiting amino acids in a diet must be known (Jin et al, 1998). The National Research Council's "Nutrient Requirements of Swine" (1998) is the most current summary of relevant nutrition research for all stages of swine production. However, the body of research on amino acid requirements of producing sows that the NRC (1998) draws from is very limited, and several indispensable amino acids have not been re-evaluated for a considerable period (Table 2.1.2). For example, during gestation only lysine and

threonine requirements have been estimated more than once. Although the situation for lactation requirements appears somewhat better, in comparison to the number of experiments necessary to achieve satisfactory estimates in growing pigs, these numbers seem quite inadequate. Partly for this reason, the current NRC edition estimates amino acid requirements using a factorial approach, even though most of the experiments that it draws from have not determined amino acid requirements in a manner appropriate for this use.

Our swine population is subject to continuous genetic pressure (Fuller, Beckett and Wang, 1989), thus challenging the ability of researchers to adequately describe the animal's requirements. The amino acid needs of today's sows are slightly higher for gestation and considerably higher for lactation compared to sows of ten years ago (NRC, 1988; NRC, 1998). Modern sows are much leaner, and are capable of conceiving and raising larger litters (Pettigrew, 1993; Kerr, 1997). However, current knowledge of the nutrient requirements of these animals is limited, and to formulate diets with amino acid profiles more closely matching the requirements of the sow, the amino acid requirements must be known with considerable confidence.

Table 2.1.2 Current knowledge on the amino acid requirements of sows: number of peer-refereed publications, and most recent research dates [a]

	Gestation		Lactation	
Amino Acid	**Publications**	**Most recent**	**Publications**	**Most recent**
Arginine	0		0	
Histidine	0		0	
Isoleucine	1	1990	1	1977
Leucine	0		1	1978
Lysine	> 5	2002	> 10	2000
Methionine	1	1971	4	1993
Phenylalanine	1	1990	2	1987
Threonine	4	2002	3	2001
Tryptophan	0		2	1997
Valine	1	1983	6	2000

a) information is current, to the best of the author's knowledge

2.3.1 Current Knowledge of Amino Acid Requirements

A nutrient requirement can be defined as the least amount of the nutrient that supports a specified level of production (Pettigrew, 1993). However, amino acid requirements can not be defined as an exact amount (Just, 1984), due to considerable individual animal variation (10 to 20%, depending on stage of life). This then raises the question of how to determine an amino acid requirement. Amino acid requirements for growing swine are generally determined by growth data, however such data is meaningless in adult animals (Baker, 1986). With sows, reproductive function must also be considered (Pettigrew, 1993). Currently, two main methods have been employed to determine amino acid requirements; empirical methods, and the factorial approach. Because it is typically first limiting in swine diets, lysine has been the most investigated amino acid under both of these approaches (Boyd et al, 2000; Nelssen, 2000).

Empirical studies employ graded levels of an amino acid, holding all other nutrients constant, and select the requirement as the level giving optimal performance (Pettigrew, 1993). Although these studies connect requirement recommendations with actual animal performance, they only demonstrate the requirement of the population in which the experiment was carried out (Pettigrew, 1993). Additionally, to accurately estimate responses of the general population, large numbers of animals must be studied. Standard empirical methods for determining amino acid requirements include nitrogen balance, and comparative slaughter techniques. Nitrogen balance has been the most frequently employed method to measure lysine requirements of gestating sows (Dourmad and Etienne, 2002).

With the increasing genetic diversity present in modern swine herds, there is growing emphasis on defining nutrient requirements using the factorial approach (Cooper et al, 2001). The factorial approach estimates amino acid requirements for specific physiological functions, namely maintenance, milk production, and protein accretion. Factorial estimates assume that the efficiency of nutrient utilization is constant over a wide range of nutrient intakes (Pettigrew,

1993) and that factors not considered do not have an effect; assumptions that are likely incorrect for pregnant and lactating sows, but are difficult to evaluate. Studies in humans have indicated that metabolic efficiency is enhanced during the pregnant state, compared to the non-pregnant, non-lactating state (Baird, 1986; Illingworth et al, 1987), possibly through the steroidal placental hormones (Baird, 1986); an adaptation which likely occurs in sows, as well. Indeed, one study examining energy utilization in pregnant sows noted that the efficiency of protein deposition was higher in pregnant sows than in non-pregnant animals of the same age and body weight (Close et al, 1985). Ignoring these observations, amino acid requirements of sows have been described using the factorial approach. The NRC (1998) utilized computer models to develop factorial estimates of amino acid requirements for gestating and lactating sows. Requirements for lysine were derived from results of a variety of empirical and factorial experiments. The requirements for all other amino acids were determined using assumed ideal protein ratios for maintenance, protein accretion and milk production, as well as body tissue for lactating sows. Because there is currently little data for sows, amino acid requirements for maintenance and protein accretion were extrapolated from growing pig studies (NRC, 1998; Dourmad and Etienne, 2002). Similarly, the ideal ratio of amino acids in body tissue was determined after a review of growing pig literature (Pettigrew, 1993). The requirement for milk production was calculated using the ratio of amino acids in milk protein given by Pettigrew (1993), modified for valine, to reflect recent research (NRC, 1998). While appearing to simplify estimations of amino acid requirements, the scarcity of relevant sow information to base these computer models on makes their estimations inherently flawed. Therefore, factorial estimates of amino acid requirements of gestating and lactating sows should be regarded with considerable caution, until the assumptions upon which the factorial estimates are based are verified experimentally.

Aside from lysine, there is little recent work on amino acid requirements of gestating sows. Dourmad and Etienne (2002) recently estimated lysine and threonine requirements of

gestating sows using nitrogen balance. Additionally, these researchers extrapolated their results to estimate the lysine requirement at maintenance, and found it to be lower than that for growing pigs.

There has been much more emphasis on determining the amino acid requirements of lactating sows. Several indispensable amino acids including lysine (Touchette et al, 1998; Yang et al, 2000a), threonine (Cooper et al, 2001), valine (Richert et al, 1996; Carter et al, 2000) and the branched chain amino acids (Moser et al, 2000) have recently received attention. Most researchers determined the requirement to be the amino acid level resulting in maximal litter growth, whereas Touchette et al (1998) used minimal sow weight loss as the indicator of requirement. The tryptophan needs of sows receiving synthetic lysine was also evaluated using sow weight loss as an indicator of requirement (Libal et al, 1997). Most estimates fall close to the amino acid requirements given by NRC (1998), however, some of the estimated valine requirements (Richert et al, 1996; Moser et al, 2000) are higher than those of NRC (1998).

2.3.2 Amino Acid Requirements During Gestation

The majority of experiments on individual amino acid requirements for gestating sows were conducted at least fifteen years ago (Easter and Kim, 1998). The more recent development of computer models of gestation metabolism have helped to more accurately describe the amino acid requirements of gestating sows. The NRC (1998) utilizes these models to predict the nutrient requirements of gravid sows. With knowledge of the sow's body weight at breeding, estimated total gestation weight gain, desired lean tissue gain during gestation (Pettigrew, 1993) and anticipated number of piglets born, individual amino acid requirements for gestation are calculated by the model. These models still only provide an estimate, and because they contain many unverified assumptions, thus do not invalidate the need for animal experiments. Among these assumptions are: that the ideal protein pattern for maintenance and daily maintenance requirement for true ileal digestible lysine is the same as for growing pigs; the digestibility of

amino acids is similar for growing pigs and sows in a corn-soybean meal diet; the amino acid requirements for observed milk production also maximize subsequent reproductive performance; and the ratio of amino acids required for milk production is accurate (NRC, 1998).

These models are used and accepted, despite unverified assumptions, because accurately determining amino acid requirements of producing sows is complicated and difficult. The amino acid needs of the sow are not static through gestation, and are influenced by environment, genetic potential, body condition (indicating current and previous nutritional status), and body composition (Pettigrew, 1993; Pettigrew and Yang, 1997). The sows' total requirement for amino acids is comprised of separate requirements for maintenance, maternal growth and fetal growth (Nelssen, 2000). Maternal gain is the most variable factor, due to large differences in genetics, age and previous nutritional influences (Pettigrew, 1993). As expected maternal tissue gains increase, so does the requirement for each amino acid (Nelssen, 2000).

Priority is given to maintenance and pregnancy before maternal gain (Mahan and Mangan, 1975), however the relative proportion of these factors does not remain constant. During the last trimester (day 75 to parturition), fetal growth is considerable (Noblet et al, 1997; Nelssen, 2000), and rapid protein accretion occurs in the mammary glands in preparation for milk production (Kusina, 1999a). It is reasonable to assume that the balance of amino acids required in the later stages of pregnancy is different from that needed in early pregnancy, when maternal growth comprises a larger proportion of the overall requirement. King and Brown (1993) noted that crude protein needed by gilts, to maximize nitrogen retention, decreased at mid pregnancy, and then greatly increased as gestation progressed. This increased protein requirement during late gestation can largely be attributed to the increased needs of the conceptus, which requires four times as much protein per day during late gestation as compared to the first trimester (Nelssen, 2000). This scientific evidence, however, is not reflected in the recommended amino acid concentrations stated in the current NRC (1998) model, which provides a single amino acid concentration for the entire gestation period.

Accurate determination of amino acid requirements during gestation is confounded by the apparent ability of the sow to alter the priority of the factors that comprise the total requirement. First parity sows experiencing considerable weight loss during the prior lactation will demonstrate a priority for maternal gain, exhibiting compensatory growth in the first trimester of the subsequent gestation (O'Grady and Hanrahan, 1975). This high rate and efficiency of weight gain is not observed with animals not losing considerable weight in lactation. This phenomenon, however, may be mainly associated with younger sows, because compensatory gain was not observed in multiparous sows losing over 30 kg of maternal tissue during lactation (Dourmad et al, 1996). One theory proposed by Everts and Dekker (1994) to explain this occurrence is that sows attempt to reach a preset amount of body protein, and that once achieved, this process is no longer a priority. However, because 30 to 40% of the sow herd qualifies as young sows (first or second parity), this means that the current model cannot accurately estimate requirements for a large portion of the herd.

In addition, there is evidence that fetal growth is not entirely dependent on nutrients supplied by the feed during gestation. Maternal tissues are capable of buffering amino acid deficiencies to maintain and support fetal growth (Mahan, 1977). Even under severe energy and protein malnutrition, pregnancy is maintained (Noblet et al, 1997), although piglet birth weight is reduced. This ability to sustain pregnancy while experiencing amino acid deficiency makes accurate estimation of requirements very difficult (Easter and Kim, 1998).

Gestation nutrition, however, does appear to influence lactation weight loss (Sinclair et al, 2001) and performance. Milk yield in early lactation is mainly dependent on gestation nutrition, while later yields depend more upon lactation feed intake (Revell et al, 1998b; Kusina et al, 1999b). The capacity of a nursing sow to utilize tissue-derived amino acids to support milk production depends on the size of her reserves, and thus her previous nutritional status. Gestation diets deficient in amino acids do not optimize nitrogen retention, resulting in the sow entering lactation with insufficient protein reserves to optimize performance (Willis and

Maxwell, 1984). Deficiencies in gestation can be compensated for by feeding higher amounts of protein in lactation (Everts and Dekker, 1995), however, if feed intake during lactation remains low, previous gestation nutritional status can become a significant determinant of sow and litter performance.

2.3.3 Amino Acid Requirements for Lactation

Lactation is a highly complex biological state, characterized by an incredible capacity of the sow to support litter growth through considerable production of milk. Amino acid requirements of lactating sows are of primary concern for producing sufficient milk to support satisfactory litter growth (Hurley et al, 2000). The amino acid requirements for lactation are often considered to be those for maintenance plus maximal milk production. Because the mammary gland is actively growing during lactation, amino acid requirements for sows must also account for this demand (Kim et al, 1999).

Modern sows are capable of milk yields greater than 10 kilograms per day (Boyd et al, 2000), an increase of 25% from sows ten years previously (NRC, 1988). Because milk production is dependent upon litter size (Kim et al, 2001), larger litter sizes combined with an increased ability to produce milk are likely responsible for this increased milk output (Boyd and Kensinger, 1998). Substrates for milk synthesis arise from both dietary sources and body reserves (Revell et al, 1998b). The mammary gland is the major user of absorbed nutrients, utilizing over 90% of the absorbed amino acids (Boyd and Kensinger, 1998) and 70% of the total energy requirement (Eissen et al, 2000). Normally, nearly 80% of the lysine found in milk protein is derived from dietary sources (Hurley et al, 2000). Therefore, to maximize milk production and minimize maternal tissue breakdown, the sow must be provided with sufficient dietary nutrients. If the diet cannot supply sufficient indispensable amino acids for milk synthesis, the sow will catabolize maternal tissues to provide them, until a critical amount of

maternal protein has been lost. Therefore, the contribution of maternal tissue to circulating amino acids will depend greatly on the nutritional status of the sow.

Amino acid nutrition is especially important during the early stages of lactation, as nearly half of the total body protein lost during a 21-day lactation occurs in the first week (Boyd et al, 2000). This contribution of amino acids from maternal tissue for milk synthesis complicates accurate determination of amino acid requirements (King et al, 1993), because the amino acid profile arising from the catabolism of body protein (Table 2.1.1) will be different from that provided by the diet. The dietary requirement for each amino acid will then be altered, depending on the degree of maternal tissue catabolism. While the NRC tables (1998) do include sow weight loss as a factor in the determination of amino acid requirements during lactation, recommendations are limited to either no loss or a preset loss of ten kilograms. Additionally, a computer model is provided with the current NRC (1998), enabling the user to calculate requirements at variable feed and energy intakes, and weight changes, however, the model is based on limited experimental data.

Ideally, an optimum ratio of dietary amino acids will provide a correct balance of each of the indispensable and dispensable amino acids needed to maximize milk protein and minimize maternal loss. However, it appears that there are two distinct requirements for amino acids within lactation (O'Grady and Hanrahan, 1975; King et al, 1993; Nelssen, 2000). The amino acid concentrations required to minimize body protein loss are higher than those necessary to maximize milk yield and litter gain for both traditional (O'Grady and Hanrahan, 1975) and modern sows (King et al, 1993; Nelssen, 2000). Thus, in the interest of clarity, the criteria utilized in determining individual amino acid requirements should be standardized (Tokach et al, 1992a; Touchette et al, 1998). Such criteria may include: determining requirements under adequate energy intake, using similar diet formulation methods (i.e. intact proteins vs. free amino acid inclusion) when determining requirements, and using the same

measurement to express the requirement (i.e. for lactating sows, using either minimal sow weight loss, or maximal litter growth).

The requirement for lysine during lactation has been extensively evaluated, because it is typically the first limiting amino acid for lactating sows (Wilkinson et al, 1984; Kerr, 1997). The other indispensable amino acids have been given less consideration. Although limited in it's accuracy, application of the ideal protein concept in the estimation of requirements for the other indispensable amino acids has been suggested (Easter and Kim, 1998). One must be cautious in this approach, however, because, as previously discussed, the ideal ratio of amino acids required by the sow will not be static (see section 2.2).

Recent evidence indicates that the mammary gland extracts several amino acids from the arterial circulation in greater quantities than found in milk protein (Trottier et al, 1994); notably the branched chain amino acids (valine, isoleucine, leucine) and arginine (Trottier et al, 1997). Valine, in particular, is extracted from the arterial circulation 30% in excess of what appears in the milk. It is unclear what the mammary gland uses these amino acids for, aside from milk production, but it is theorized that some are utilized for mammary tissue accretion, are oxidized to provide energy for lactose and fatty acid synthesis, or transaminated to form dispensable amino acids (Trottier et al, 1997). The NRC (1998) does account for the initial results of Trottier et al (1997) in its recommendations for amino acid inclusion rates during lactation; however, this discovery has forced the re-evaluation of current amino acid estimates for modern sows.

As stated above, amino acid requirements during lactation are closely related to the production of milk (Carter et al, 2000). Milk yield is linearly related to the number of piglets nursing (Revell et al, 1998b) such that each piglet is assumed to cause an increase in milk production of 0.96 kg per day (King et al, 1989; Stahly et al, 1992). Thus, it is reasonable to assume that the lysine requirement of high producing sows is higher than that of average sows simply due to increased milk production (Nelssen, 2000). The requirements for several amino

acids, including lysine and valine, appear to be dependent on milk production of the sow, however both linear (Richert et al, 1997a,b) and quadratic relationships (Yang et al, 2000a) have been described.

In an attempt to better understand specific amino acid requirements of high producing sows, several researchers have evaluated the effect of supplying lysine and valine concentrations greater than that recommended in NRC (1988) on sow and litter performance. Increasing lysine concentrations above NRC (1988) recommendations for lactating sows has given variable results. Some studies have reported no effect of increased lysine on litter growth rate (Knabe et al, 1996; Touchette et al, 1998), while others have demonstrated marked increases in growth rate (Richert et al, 1997b; Yang et al, 2000a). Similarly, sow weight loss has been shown to decrease with dietary lysine increases (Richert et al, 1997b; Touchette et al, 1998), or has shown no response to increasing lysine concentrations (Knabe et al, 1996; Yang et al, 2000a).

Valine has recently been implicated as potentially limiting in the diets of high producing sows (Richert et al, 1996). Increasing dietary valine while maintaining constant lysine concentration increased litter weights and weight gains for high producing sows (Richert et al, 1996; 1997b; Moser et al, 2000) in some instances, but not in others (Boyd et al, 2000; Carter et al, 2000). Increases in dietary valine with constant lysine concentrations, however, do not affect sow weight loss (Richert et al, 1996; 1997b; Carter et al, 2000). Richert et al (1996) also noted that plasma urea nitrogen increased with valine addition. Due to this, Trottier (1997) theorized that the increase in performance with supplemental valine might be related to some property of valine itself, rather than as a limiting amino acid for protein synthesis. It has been speculated that high plasma valine may stimulate alanine production and release from muscle, potentially stimulating gluconeogenesis, and thus, glucose supply to the mammary gland (Richert et al, 1996).

The response of sows to amino acid supplementation of apparently adequate diets seems to depend on the productive demands placed on the sow. Richert et al (1997b) observed that increasing the lysine and valine concentrations in the diet had a greater effect on sow and litter performance for sows nursing ten or more piglets than for those sows nursing fewer than ten. Interestingly, diet composition also appears to affect the response to increased lysine. Addition of crystalline lysine to a sorghum-soybean meal diet, formulated on a total amino acid basis, improved piglet weaning weights while no response to lysine was found for a corn-soybean meal diet supplemented with crystalline lysine to the same level as found in the sorghum diet (Knabe et al, 1996). Therefore, an amino acid other than lysine probably limited performance in the corn-soybean meal diet, likely tryptophan and /or threonine.

2.3.4 The Influence of Protein: Energy Interactions on Sow Amino Acid Requirements

The requirements for energy and amino acids are closely linked (Edwards and Campbell, 1993), thus when making amino acid recommendations, energy content of the diet must be considered. Energy and protein supply will interact to influence protein accretion. Nitrogen retention in growing pigs increases with increasing dietary protein intake, until energy becomes limiting (Edwards and Campbell, 1993). At this level, increased protein intake will not induce greater nitrogen retention, unless energy intake is also increased. Additionally, protein and energy interact to influence body weight and backfat loss during lactation. At deficient lysine intakes, protein accounts for a greater proportion of body weight loss in lactating sows, whereas with high lysine intakes, fat accounts for a larger proportion of the loss, when energy intake is held constant (Tokach et al, 1992a).

Both energy and protein intake by the sow are important in influencing litter performance in lactation (Boyd and Kensinger, 1998; Nelssen, 2000). Energy supply is extremely important during lactation, as nearly 70% of the glucose in the body is utilized for milk synthesis (Boyd and Kensinger, 1998). With low energy intakes, increased lysine has little

effect on milk yield compared to when both energy and lysine are increased (Tokach et al, 1992a; Nelssen, 2000). Milk protein concentration has been shown to decrease with reduced protein intake (McNamara and Pettigrew, 2002). Protein and energy interact, however, such that increased energy intake can partially offset the reduction in milk protein content caused by low protein intakes (McNamara and Pettigrew, 2002).

Due to these interactions, amino acid requirements for sows should be determined under conditions of adequate energy intake. As low protein, amino acid supplemented diets become more common, observations of animal responses must consider energy adequacy as well as amino acid supply.

2.3.5 Factors Controlling Feed Intake

Voluntary feed intake is often a limiting aspect in lactating sow nutrition. Feed intake is controlled by a variety of factors, including: body composition, litter size, environmental influences such as temperature and management practices, and diet considerations of digestibility, composition, energy density and amino acid balance (Eissen et al, 2000). Feeding low protein, amino acid supplemented diets may alter body composition (see section 2.4.4). Therefore it is important to measure voluntary feed intake when providing low protein, amino acid supplemented diets, because both body composition and diet composition can directly affect voluntary feed intake. Feed intake in the first two weeks of lactation is more sensitive to maternal fat stores than to dietary crude protein content (Revell et al, 1998a). Higher body fat reserves at farrowing decrease feed intake during lactation (Eissen et al, 2000; Prunier et al, 2001); this is especially noticeable during the first week (Prunier et al, 2001). Furthermore, fat sows have lower body protein reserves to support milk synthesis in instances of low intake (Revell et al, 1998a).

Low crude protein intakes during gestation reduce lactation feed intake if dietary protein content of the lactation diet is also low (Mahan and Mangan, 1975). Decreased feed

intake is not observed when higher protein diets are fed during gestation, indicating that milk production, and thus the drive to consume feed, is likely reduced in sows with limited protein reserves. Additionally, amino acid imbalances can influence feed intake. Uttecht et al (1991) noted that marginal or limiting levels of tryptophan have a negative effect on feed intake. Similarly, lactating sows fed lysine at 30% of their requirement demonstrated lower feed intake than sows fed adequate lysine (Jones and Stahly, 1999). With low protein, amino acid supplemented diets, however, we attempt to control these factors and provide a balance of amino acids to support milk synthesis and prevent maternal tissue loss.

The factors that influence feed intake in gestating sows are not as difficult to account for as with the lactating sow, due to the standard practice of feeding gestating sows restrictively to control body weight. Feed intake, however, is extremely important in lactating sows, because they frequently have a tendency for low appetite. Feed intake of growing swine fed a low protein, amino acid supplemented diet has been shown to match (LeBellego et al, 2002) or exceed (Quinou et al, 1995) that of growers fed standard protein diets. Feeding low protein, amino acid supplemented diets to lactating sows has generally elicited similar results. Sows fed diets decreased in crude protein content up to 4 percentage units, but with adequate amino acid supplementation, demonstrated daily feed intakes similar to their conventionally fed counterparts (Renaudea et al, 2001 (6.5 vs. 6.7 kg); Johnston et al, 1999 (6.3 vs. 6.4 kg)). O'Grady and Hanrahan (1975) observed similar feed intakes for sows fed amino acid supplemented diets, although sows consuming imbalanced diets showed slightly decreased intake. Alternately, Trombetta et al (2001) observed increased feed intake (4.9 vs. 4.2 kg) for sows fed a diet decreased in crude protein from 18 to 13.9% and supplemented with lysine, although this difference was not statistically significant.

Because feed intake of lactating sows fed low protein, amino acid supplemented diets is similar to, or greater than sows fed conventional diets, deficiencies of amino acids and energy will not occur, provided the low protein diet is properly formulated. Likewise, performance of

sows fed low protein, amino acid supplemented diets during lactation is expected to be similar to sows fed conventional diets, because sows fed a low protein diet should consume sufficient nutrients for maximal milk production. However, how well the ingested nutrients, in low protein, amino acid supplemented diets are digested and utilized by sows is not clearly known.

2.3.6 Relationship Between Feeding Frequency and Utilization of Amino Acids in Supplemented Diets

There is concern that amino acid supplemented diets are utilized less effectively than intact protein diets when fed infrequently, which is the situation with gestating sows. Digestive processes, however, do not appear to be influenced by feeding frequency. When feeding a lysine-supplemented diet once versus twice daily to gravid gilts (Kerr and Easter, 1986), or twice versus seven times per day to growing pigs (Le Bellego et al, 2001), nutrient digestibility was similar, regardless of meal frequency.

Some evidence exists, however, that low protein diets, fed infrequently to growing pigs, will create an imbalance of amino acids at the sites of metabolism (Batterham and Murison, 1981; Batterham and Bayley, 1989). Crystalline amino acids pass through the stomach shortly after feeding (Bach Knudsen and Jørgensen, 1993) and are rapidly absorbed by the gut. Intact proteins must first undergo proteolysis before the majority of amino acids are released and can be absorbed. Much of the synthetic lysine may be wasted if absorbed several hours ahead of the amino acids from intact proteins (Baker, 1986). Canolty and Nasset (1975) noted that, in rats, 25 to 40% more of the free than protein bound methionine is absorbed in the first 15 to 60 minutes after a meal. These differences, however, appear to be restricted to the first 2 to 3 hours post-meal (Rerat, 1985). While the absorption coefficient (amount absorbed/ amount ingested) is higher for free amino acids at one hour after feeding, the coefficients are similar by three hours after feeding regardless of amino acid source (Rerat, 1985).

Absorption rate only provides an indication of how quickly amino acids are extracted from the gut, and is not an indicator of amino acid sufficiency for metabolic processes. There is no storage mechanism for excess amino acids; however, liver proteins can function as a short-term pool of amino acids (Kerr and Easter, 1986), enabling the animal to make use of the quickly absorbed synthetic amino acids. Additionally, nitrogen absorbed from the intestinal tract accounts for less than half of the amino acids used for protein synthesis (Reeds et al, 1980). Several growing pig studies, however, have observed lower efficiencies of utilization of free lysine when animals were fed once daily as compared to more frequent feeding (Batterham and Murison, 1981; Partridge et al, 1985). When lysine supplemented diets were fed more frequently (greater than once daily), the efficiency of utilization was similar, although no added benefit to feeding more than twice daily was observed (Partridge et al, 1985). Although these observations could be attributed to the presence of free amino acids, similar decreases in performance are observed with once daily feeding of conventional diets (George et al, 1988; Bach Knudsen and Jørgensen, 1993), indicating that metabolic processes rather than poor utilization of free amino acids may account for these differences. Similarly, Partridge et al (1985) noted that feeding frequency influenced the efficiency of nitrogen utilization of growing boars, regardless of the presence or absence of free lysine. In pregnant gilts, however, nitrogen retention was not clearly influenced by synthetic lysine supplementation or meal frequency (Kerr and Easter, 1986). These observations may be important when feeding diets containing synthetic amino acids to gestating sows, because it is common practice to provide feed in once daily meals. However, to the author's knowledge, experiments to determine if free amino acids are efficiently used in gestating sows fed once daily, have not been described in the peer-refereed literature.

2.4 Physiological Effects of Feeding Low Protein, Amino Acid Supplemented Diets

Simply stated, "supplemented amino acids must be fed at the proper level, at the proper time and with the proper level of all other essential amino acids" (Jin et al, 1998).

2.4.1 Digestibility of Low Protein, Amino Acid Supplemented Diets

Some evidence exists that protein digestion and utilization are altered with amino acid supplementation. Protein digestibility in grower pig diets has been shown to decrease (Sharda et al, 1976; Just, 1982; Noblet et al, 1987; Gatel and Grosjean, 1992; Kerr and Easter, 1995; Möhn and Susenbeth, 1995; Heger et al, 1997) with decreasing crude protein contents. However, others have found no effect of reducing dietary crude protein on energy (Le Bellego et al, 2001; Gomez et al, 2002) or nutrient digestibility in grower pig diets (Le Bellego et al, 2001; Gomez et al, 2002; Lee et al, 2001). Similarly, the digestibility of protein in amino acid supplemented, low protein sow diets was not different from the protein digestibility in the conventional diet (Cuaron et al, 1984; Kerr and Easter, 1986). The amino acids in soybean meal, the main protein source used in swine diets, are more digestible than those in grains such as barley, wheat and corn. As low protein diets typically contain lower concentrations of soybean meal and higher concentrations of grains, it is reasonable to assume that these diets would be less digestible than conventional diets. However, the presence of synthetic amino acids, which are generally considered to be 100% digestible, enhances the total digestibility of amino acids (Han and Lee, 2000). It is noteworthy that amino acid digestibilities of feedstuffs are usually measured in growing pigs. Evidence exists that sows are capable of more completely digesting the amino acids in a feedstuff (Stein et al, 1999), enabling them to utilize feed protein to a greater extent. However, the quantity of research on amino acid digestibility by producing sows is extremely limited (Stein et al, 1999). Stein et al (1999) found that the pattern of amino acid digestibility, relative to lysine, in many feedstuffs, is different in sows than in growing pigs. Additionally, these authors speculated that sows probably have a different

loss of endogenous amino acids, which would also affect amino acid requirements. For sows, this increased apparent digestibility of indispensable amino acids in grain sources may partially offset the quicker absorption of free amino acids in low protein diets. To verify this, additional research should be conducted on nutrient digestibility and true ileal digestible amino acids in feedstuffs for sows.

2.4.2 Intermediary Metabolism of Nitrogen in Amino Acid Supplemented, Low Protein Diets

Surplus dietary amino acids are deaminated by the body, and their nitrogen excreted in the urine as urea (Wilkinson et al, 1984). By feeding low protein diets, supplemented with limiting amino acids, the total intake of indispensable and dispensable amino acids is reduced. Provided that the requirement for each indispensable amino acid is met, reduction of excess amino acids should decrease the amount of urea nitrogen excreted from amino acid catabolism. When properly formulated, amino acid supplemented, low protein diets reduce nitrogen excretion without affecting nitrogen retention and weight gain in growing pigs (Le Bellego et al, 2002). On occasion, improved nitrogen retention on a low protein, amino acid fortified diet has been observed (Tachibana and Ubagai, 1997), which suggests that the nitrogen in reduced protein diets is used with an efficiency equal to or greater than the nitrogen in conventional diets. Decreased nitrogen retention has also been observed (Kerr and Easter, 1995; Lee et al, 2001) in growing pigs fed a low protein diet, supplemented with limiting amino acids. The efficiency of nitrogen retention of these pigs, however, was greater than (Lee et al, 2001) or similar to (Kerr and Easter, 1995) that of pigs fed the standard diet.

Generally, reducing crude protein content of the diet by one percentage unit (e.g. from 16 to 15% CP), while maintaining amino acid adequacy, will result in a concomitant decrease in urinary nitrogen excretion of seven to eleven percent, with an average decrease of eight percent, regardless of physiological state (Jongbloed and Lenis, 1992; Kerr et al, 1995; Kerr and Easter,

1995; Sutton et al, 1999; Lee et al, 2001; Renaudeau et al, 2001). The decrease in total nitrogen excretion (fecal plus urinary) is mainly due to the decrease in urinary nitrogen excreted (Le Bellego et al, 2001; Lee et al, 2001), indicating a reduction in degradation of amino acids. Because the urea nitrogen in urine is easily converted to ammonia, nitrous oxide, and other nitrogenous compounds, decreases in excreted urinary nitrogen will also lead to reduced ammonia volatilization, and nitrogen loss from manure applied to farmland.

Because nitrogen metabolism responds quickly to changes in dietary amino acid content (Kerr, 1997), changes in plasma urea can be used to determine the order of limiting amino acids in a diet (Cervantes et al, 1995) and to determine amino acid requirements for specific physiological states (i.e. lactation) (Kerr, 1997). Lactating sows fed low protein diets exhibit dramatically reduced blood urea nitrogen concentrations compared to animals fed conventional protein levels (Tokach et al, 1992b; Falaschini et al, 1994), similar to growing pigs (Kerr and Easter, 1995; Lee et al, 2001), indicating a reduction in amino acid deamination. Similarly, milk urea concentrations are greatly reduced in sows fed diets reduced in protein, and supplemented with synthetic lysine, methionine, tryptophan and threonine (Falaschini et al, 1994). Since urea has no known nutritional values for piglets (Wu and Knabe, 1994), reduced milk urea may improve the metabolic status of nursing piglets. Similarly, the concentration of plasma amino acids rises when amino acids are supplied above the requirement of the animal (Wilkinson et al, 1984). By reducing this surplus, plasma free amino acid concentrations would be expected to decrease. The limited experimental evidence in lactating sows (Mennenga, 1986) indicates, however, that plasma amino acid concentrations are not primarily dependent on dietary amino acid supply, which is the case in growing pigs; and are affected by protein turnover rates, amino acid recycling, and oxidation. When reducing dietary crude protein from 14 to 11% and supplementing lysine and tryptophan, only threonine and valine (of the indispensable amino acids) were reduced in the plasma.

The majority of the available data on intermediary metabolism of nitrogen in pigs has been collected in growing swine. While experimental results indicate that sow response is similar to that of growing pigs, available data is limited, and further research in this area is needed.

2.4.3 Intermediary Metabolism: Energy

A significant portion of the metabolizable energy from catabolized dietary protein cannot be utilized by the sow (50%), because catabolism of excess amino acids results in increased heat production and energy losses in urinary urea (Just, 1982; 1984). Feeding diets lower in crude protein, supplemented with amino acids could potentially reduce this energy loss, and make sows more energy efficient. Experimental evidence in growing pigs indicates that the energy excreted in urine can be reduced by 3.5 kilojoules (kJ), for each one-gram decrease in protein intake (Le Bellego et al, 2001) and 28.4 to 30.6 kJ for each one-gram reduction in urinary nitrogen (Just, 1982; LeBellego et al, 2001). As well, energy lost as heat decreases by 7 kJ for each gram decrease in crude protein intake. At similar metabolizable or digestible energy intakes, low crude protein diets reduce total heat production, mainly due to a reduction in the thermic effect of feeding (Le Bellego et al, 2001). In this manner, low crude protein diets are also low heat increment diets (Le Bellego et al, 2002). As less of the ingested energy is lost, animals fed low protein diets will have a lower energy requirement, when expressed on a digestible or metabolizable energy basis (Le Bellego et al, 2002), than animals fed a conventional diet.

The sow is unable to utilize all of the metabolizable energy from the catabolism of excess dietary amino acids, resulting in a reduction of energy available for metabolic processes, thereby causing the sow to utilize dietary metabolizable energy inefficiently. If the sow is provided with amino acids (esp. lysine, threonine, methionine, and tryptophan) in a profile that more closely meets her amino acid requirements for gestation or lactation, then the amount of

excess amino acids should be reduced, and the amount of dietary energy expended on the deamination of excess amino acids, and subsequent synthesis and excretion of urea in urine also decreased.

Reducing urinary energy and heat losses from the catabolism of protein increases the amount of energy available for tissue deposition (Le Bellego et al, 2001; Le Bellego et al, 2002). Growing pigs fed low protein diets often retain more energy as fat than those fed a commercial diet (Quiniou et al, 1995; Kerr and Easter, 1995; Möhn and Susenbeth, 1995). This increased retention may lead to increased carcass fatness observed by some researchers. However, this raises the concern of how to properly formulate low protein diets for sows to account for the apparent differences in energy utilization.

Considering the efficiency of utilization of the metabolizable energy found in starch and protein (0.82 vs. 0.58; LeBellego et al, 2001), it is evident that the energy in starch is used more efficiently by the body than the energy in protein. Protein has a lower net energy value than starch, because oxidation of protein increases the energy lost in urine and as heat (Just, 1982). As protein is decreased in the diet, carbohydrates will increase proportionally, and it is reasonable to assume that the energy in low protein diets will be utilized more efficiently than the energy in conventional diets. If true, sows fed low crude protein diets will exhibit reduced heat losses and demonstrate better energy utilization than their conventional fed counterparts. Studies in growing pigs have indicated that for each percentage decrease in crude protein content of the diet a concomitant 0.6% increase in net energy content occurs (Lee et al, 2001). For this reason, low protein diets should be formulated on a net energy basis to account for the increased efficiency (Le Bellego et al, 2002). Net energy more accurately describes the energy available for body processes (Edwards and Campbell, 1993), unlike digestible or metabolizable energy, which measure the energy digested or absorbed by the animal. These energy related issues have been examined in growing pigs fed low protein diets, however, no comparable research has been conducted in sows.

Voluntary feed intake of lactating sows is often insufficient to meet their energy requirements (Noblet et al, 1990), causing them to be in negative energy balance throughout lactation. Energy balance is especially negative during the first six days of lactation, when feed intake is often regulated through management procedures (Boyd et al, 2000), and during the third or fourth week of lactation (Noblet et al, 1998), when energy output in milk exceeds energy intake. Because sows fed low protein, amino acid supplemented diets should consume more net energy per kilogram of feed than sows fed a conventional diet, low protein diets could be used to help alleviate the effect of inadequate feed intake during lactation on energy balance. This increased energy efficiency exhibited by sows fed low protein, amino acid supplemented diets may be beneficial when sows are maintained in hot environments. Sows housed in high environmental temperatures (e.g. 29°C) exhibit reduced voluntary feed intake, likely in an attempt to reduce the thermic effect of feeding (Renaudeau et al, 2001). With low feed intake, deficiencies in energy intake can occur, leading to extensive tissue catabolism (Boyd et al, 2000), reduced milk production (Renaudeau and Noblet, 2001), and lower piglet weaning weights (Johnston et al, 1999). By feeding low protein, amino acid supplemented diets, the negative effects of high temperature on energy intake and body weight loss may be attenuated (Renaudeau et al, 2001), because sows fed low protein diets will consume more energy than conventionally fed sows, at similar feed intakes. Renaudeau et al (2001) noted that, when housed at 29°C, sows fed a low protein diet consumed similar amounts of feed, but exhibited lower weight loss during lactation than sows fed a conventional diet, indicating that sows fed the low protein, amino acid supplemented diet were less nutritionally stressed. However, feeding diets reduced in crude protein in hot environments may benefit the sow more than her litter. Similar piglet performance at 29°C was observed, regardless of whether sows were fed low protein or conventional diets (Renaudeau and Noblet, 2001). Alternately, Johnston et al (1999) observed slightly higher daily gains and weaning weights for piglets nursing sows fed low protein diets at 29°C, compared to piglets from sows fed a conventional diet.

2.4.4 Changes in Body Composition

Changes in body composition occur rapidly in response to changes in protein content of the diet (Quiniou et al, 1995). Several studies have noted increased carcass fatness in growing swine fed low protein, amino acid supplemented diets (Kerr and Easter, 1995; Kerr et al, 1995; Lee et al, 2001). However, others have noted no effect of dietary protein on backfat thickness or carcass characteristics (Myer et al, 1996; Tachibana and Ubagai, 1997; Tuitoek et al, 1997b). Increases in carcass fatness are exhibited more often when dietary crude protein is decreased by four percentage units or more (Han et al, 2001), which suggests that energy balance is altered with severe decreases in dietary crude protein. When an imbalance of amino acids is provided in the diet, some amino acids are not usable for protein synthesis; they will be degraded and their carbon skeletons utilized for fat synthesis. Alternately, Lenis and Jongbloed (1999) suggested that increased carcass fatness might be due to increased net energy content of low protein diets, because less energy is expended in the deamination of excess amino acids.

Interestingly, growing pigs fed low protein, amino acid supplemented diets exhibit lower pancreas (Ward and Southern, 1995), heart, kidney, and liver weights (Kerr et al, 1995). These changes may be due to alterations in metabolism (Kerr et al, 1995), possibly through lower enzyme activity (Lenis and Jongbloed, 1999). Furthermore, with decreased organ weights, energy metabolism and body composition could be profoundly influenced, (Kerr et al, 1995) through a reduction in heat production associated with the thermic effect of feeding (Le Bellego et al, 2001).

Caution must be taken when using results from growing pig studies to predict body composition responses in producing sows, because the two groups are physiologically dissimilar. Feeding diets deficient in amino acids has been shown to alter the composition of body weight gain in sows. Kusina et al (1999b) observed that gestating sows fed a diet deficient in lysine gained more backfat and less lean tissue than sows fed a diet with sufficient amino

acids. Body weight gain was not altered when low protein gestation diets, supplemented with amino acids were fed, compared to conventional diets (Corley et al, 1983; Cuaron et al, 1984), however the composition of the weight gain was not specifically examined. During nitrogen balance experiments, Corley et al (1983) noted decreased nitrogen retention and similar body weight increases with the low protein gestation diet, compared to sows fed an intact protein diet. This would suggest that sows fed the low protein diet had increased body fat. Alternately, Cuaron et al (1984) found similar nitrogen retention for sows fed a conventional diet, or a basal diet made isonitrogenous with glutamic acid, and supplemented with lysine and threonine. Both experiments, however, fed these diets during the later stages of gestation only, when fetal growth is high.

Loss of maternal tissue during lactation is common, because sows are often incapable of ingesting sufficient nutrients to completely support milk synthesis. The degree of weight lost during lactation is dependent on the crude protein content of the diet (Revell et al, 1998a), and in situations of inadequate amino acid intake, body weight loss can be substantial (Jones and Stahly, 1999). Additionally, the composition of the weight lost in lactation, is dependent on diet composition (Brendemuhl et al, 1989). Sows mobilize maternal protein when restricted in protein or energy intake, while backfat loss is more dependent on energy intake (Brendemuhl et al, 1989). Diets with reduced protein content, containing adequate amino acid supplementation, mostly do not alter the degree of maternal tissue loss during lactation (Falaschini et al, 1994; Johnston et al, 1999; Renaudea et al, 2001; Trombetta et al, 2001), compared to conventional diets. Furthermore, the composition of this loss did not differ between low protein, and conventionally fed sows, as indicated by similar changes in backfat (Johnston et al, 1999; Renaudeau et al, 2001). One study, however, did note an increase in maternal weight loss, with no change in backfat loss, when the crude protein content of the diet was reduced from 15.8 to 12.6% and supplemented with lysine, valine, threonine, tryptophan and valine (Tokach et al, 1992b). These observations are important to note, if low protein diets are to be commercially

implemented, because body weight and composition changes can significantly affect sow reproductive performance (Clowes, 2001).

2.5 Application of Low Protein Diets

2.5.1 Low Protein Amino Acid Supplemented Diets for Sows

Information on the effect of feeding low protein, amino acid-supplemented diets to gestating and lactating sows is limited, but promising. During gestation, low protein corn-based diets supplemented with lysine and tryptophan support similar maternal weight gains as conventional diets (Corley and Easter, 1980) in second parity sows. Gestation nutrition is known to affect initial milk production (Corley et al, 1983) and maternal weight loss during lactation. However, piglet weaning weights and sow weight loss during lactation were not affected when sows were fed a low protein diet in gestation, compared to a standard diet (Corley and Easter, 1980), demonstrating that the low protein diet provided adequate amino acids to support maximal milk production and prevent excessive maternal tissue catabolism. Diets moderately low in crude protein fed during gestation did not affect the number of piglets born (O'Grady and Hanrahan, 1975; Pettigrew and Yang, 1997), although amino acid imbalances during lactation may decrease subsequent litter size (Boyd et al, 2000). Mennega (1986) did not observe a decrease in litter size when feeding a corn-soybean meal diet reduced in crude protein from 14 to 12% and supplemented with lysine and tryptophan, indicating that the diet was adequate to prevent reproductive consequences in the subsequent parity. Diets containing 3 to 4 percentage unit decreases in crude protein with supplementation of indispensable amino acids are capable of maintaining litter performance (Tokach et al, 1992b; Renaudeau and Noblet, 2001). Weights at birth and weaning of piglets that were nursing sows fed low protein diets, with supplemental amino acids were not different from the weights of piglets that were nursing sows fed conventional diets (Falaschini et al, 1994; Johnston et al,

1999; Renaudea and Noblet, 2001). Similarly, piglet growth rate was unaltered by manipulations of the sow's diet (Falaschini et al, 1994; Renaudeau and Noblet, 2001), or has been shown to be higher for piglets nursing sows receiving low protein diets, supplemented with lysine (Trombetta et al, 2001). These diets all supplied adequate amino acids, however, with minor deficiencies decreased growth rate would not be expected, due to the sow's ability to compensate for dietary inadequacies by utilizing maternal protein for milk synthesis (Noblet and Etienne, 1986). With severely inadequate dietary lysine, body protein mobilization is increased (Yang et al, 2000b) and milk production decreased. However, even moderate deficiencies may not elicit a decrease in litter growth rate with shorter lactations (Boyd et al, 2000). Slightly lower litter growth rates have been observed with a low protein diet formulated to meet NRC (1988) nutrient specifications (Johnston et al, 1999), however, when comparing the amino acid ratio in this diet to that recommended in NRC (1998), it is evident that three indispensable amino acids (threonine, tryptophan and valine) were below the currently accepted optimal ratio.

Maximal milk production, indicated by piglet growth rate, is maintained with low protein, amino acid fortified diets. Mennenga (1986) measured milk yield and found that reducing the crude protein content of the diet from 14 to 11%, and supplementing lysine and tryptophan, did not influence milk production. Similarly, when feeding sows diets reduced in crude protein by 3 percentage units, and supplemented with several indispensable amino acids, Renaudeau and Noblet (2001) calculated milk yields similar to sows fed the conventional diets. Dietary alterations in crude protein can affect milk composition. When feeding low protein diets without adequate amino acid supplementation, reduced protein content of sow's milk is a common observation (King et al, 1993; Al-Matubsi et al, 1998; Sinclair et al, 1999; Sinclair et al, 2001). However, with adequate supplementation of indispensable amino acids, low protein diets manifest milk protein contents similar to conventional diets (Mennenga, 1986; Falaschini et al, 1994; Renaudeau and Noblet, 2001).

Adequate intake of energy and amino acids is essential to minimize body weight loss during lactation. Excessive losses of body protein and fat have been shown to prolong the period between weaning and rebreeding (King and Williams, 1984; Boyd et al, 2000; Clowes, 2001), limiting the reproductive efficiency of those sows. This observation raises the concern that when the crude protein content of the diet is reduced, such as with low protein, amino acid supplemented diets, sows will be unable to consume sufficient protein to prevent excessive weight loss, and will exhibit impaired reproductive function. This concern appears unfounded, however, because lactation studies utilizing low protein, amino acid supplemented diets have not observed losses in body weight greater than that of sows fed conventional diets (Johnston et al, 1999; Trombetta et al, 2001). Additionally, decreases in crude protein content up to 4 percentage units, with adequate amino acid supplementation, do not increase the rebreeding interval (O'Grady and Hanrahan, 1975; Mennenga, 1986; Falaschini et al, 1994; Johnston et al, 1999; Renaudeau et al, 2001; Trombetta et al, 2001). Furthermore, the conception rate of sows was unaffected when feeding corn-soybean meal diets, reduced in crude protein up to 3 percentage units (Mennenga, 1986). However, reproductive failure of sows in second parity or greater would not be expected, even with protein inadequacy, due to their greater body reserves (Boyd et al, 2000).

From the available literature, it appears that low protein, amino acid supplemented diets support similar sow weight changes, reproductive efficiency, milk production, and piglet performance, as conventional diets, provided that amino acid supplementation is adequate. However, the body of research examining the use of these diets for producing sows is very limited, and commercial implementation of such diets will not occur until more research is conducted. Particularly lacking is knowledge on how much the protein content of the diet can be reduced, and if such diets can be economically implemented for sow production.

2.5.2 Limitations to Using Low Protein, Amino Acid Supplemented Diets

In a commercial setting, it is reasonable to assume that there are practical limitations to the inclusion of synthetic amino acids in the diet. One main constraint is the cost of crystalline amino acids relative to soybean meal (Han and Lee, 2000). Lysine, methionine and threonine generally can be purchased at competitive prices, depending on the current soybean meal price. The price for other crystalline amino acids is much greater, and it is currently not economical to include them in commercial diets. To obtain large decreases in crude protein content (i.e. 4 percentage units), diets must often be supplemented with other amino acids, especially tryptophan for corn-soybean meal diets. Smaller decreases, of 2 to 3 percentage units, with supplementation of several amino acids may also restrict the use of these diets in a commercial setting. Lee et al (2001) supplemented lysine, methionine and threonine or these three plus tryptophan to low protein, grower pig diets and found that diet cost per kilogram of weight gain increased by 5.5 and 7.8%, over the intact protein diet. This was in part caused by lower growth rates of pigs fed these two diets compared to pigs fed the control diet. However, one Chinese study did note a lower feed cost to kg gain ratio in 15 kg pigs fed a 15 % CP diet, supplemented with amino acids to NRC (1988) levels, compared to an 18% CP control diet (Hsieh and Chiang, 1994). Surprisingly, the economic viability of low protein diets for sows does not appear to have been evaluated.

Aside from cost, there also appears to be a biological limitation to the use of synthetic amino acids. As crude protein content is reduced, individual amino acids become sequentially deficient. The order in which amino acids become limiting depends greatly on the feedstuffs utilized and the physiological state of the pig. Depending on how severely crude protein content is decreased, supplementation of one or several synthetic amino acids may be required. Diets decreased in crude protein by one to two percentage units generally require only lysine supplementation. Low protein diets reduced by two percentage units and supplemented with

lysine appear to support similar performance as compared to conventional diets for growing pigs (Lee et al, 2001). Decreases beyond 2 percentage units generally require addition of other indispensable amino acids.

While decreases of 2 percentage units are relatively successful, decreases below this have shown variable performance. With a 3 percentage unit decrease, inferior performance in growing pigs may occur, even when limiting amino acids and nonessential nitrogen appears to be sufficient (Tuitoek et al, 1997a). At 4 percentage units below conventional protein concentrations, nitrogen excretion is dramatically reduced (Han et al, 2001), however, this degree of reduction in crude protein has often been shown to decrease average daily gain and increase backfat thickness in growing pigs (Schoenherr, 1992; Tuitoek et al, 1997a). At this level, supplementation of several amino acids, including lysine, threonine, tryptophan, methionine and possibly isoleucine and valine is required. Severe reductions in crude protein (4% or greater) may limit nitrogen retention, possibly due to a deficiency of nonspecific nitrogen (Kerr and Easter, 1995) and an imbalance of indispensable to dispensable amino acids. Decreases greater than 4 percentage units may be possible, however, provided that the proper amino acids are supplemented (Lenis and Jongbloed, 1999). To achieve this, further understanding of ideal protein ratios and whole body requirements for amino acids and nitrogen in sows and growing pigs is essential.

2.6 Summary

Low protein diets, are capable of supporting similar performance in gestating and lactating sows, provided there is adequate supplementation of limiting amino acids. However, the body of research examining low protein, amino acid supplemented diets in sows is extremely limited, and further research must be conducted before such diets will be successful enough to be widely accepted. For example, current gestation research is lacking, and, as of

yet, no studies appear to have examined feeding low protein, amino acid supplemented diets during both gestation and lactation, and during consecutive parities.

Lack of detailed empirical knowledge of the amino acid requirements, metabolism, and digestion during gestation and lactation is a main limitation to extensive utilization of low protein diets. Special attention must be given to amino acid and energy requirements when formulating low protein diets, because minor deficiencies of either can impair performance. As we improve our knowledge of how amino acid requirements are influenced by physiological state and metabolism of the sow, by environment and by diet composition, commercial use of low protein diets may become more accepted.

Increasing pressure from the public to examine the environmental consequences of intensive swine production will likely fuel further studies in this area. Even small decreases in dietary crude protein content coupled with formulation for a better balance of amino acids will result in considerable decreases in nitrogen excretion (Han and Lee, 2000). Similarly, as the price of crystalline amino acids decreases, greater quantities can be incorporated into practical swine diets without increasing feed costs.

2.7 Literature Cited

Al-Matubsi, H.Y., G. Bervanakis, S.M. Tritton, R.G. Campbell, and R.J. Fairclough. 1998. Influence of dietary protein of diets given in late gestation and during lactation on protein content and oestrogen concentrations in the colostrum and milk of gilts. Anim. Sci. 67:139-145.

ARC. 1981. The nutrient requirements of pigs. Commonwealth Agricultural Bureaux, Slough, Great Britain.

Bach Knudsen, K.E., and H. Jørgensen. 1993. Use of synthetic amino acids in pig and poultry diets. In: Recent Developments in Pig Nutrition 2 (Ed. D.J.A. Cole, W. Haresign, and P.C. Garnsworthy). Nottingham University Press, Lorghborough, Leicestershire, UK. pp. 106-116.

Baird, J.D. 1986. Some aspects of the metabolic and hormonal adaptation to pregnancy. Acta Endocrinol. Suppl. 277:11-18.

Baker, D.H. 1986. Problems and pitfalls in animal experiments designed to establish dietary requirements for essential nutrients. J. Nutr. 116:2339-2349.

Batterham, E.S., and H.S. Bayley. 1989. Effect of frequency of feeding of diets containing free or protein-bound lysine on the oxidation of [14C]lysine or [14C]phenylalanine by growing pigs. Br. J. Nutr. 62:647-655.

Batterham, E.S. and R.D. Murison. 1981. Utilization of free lysine by growing pigs. Br. J. Nutr. 46:87-92.

Black, J.L., and G.T. Davies. 1991. Ideal protein: its variable composition!. In: Manipulating Pig Production III. Australasian Pig Science Association. (Ed. E.S. Batterham) p. 111.

Boyd, R.D., and R.S. Kensinger. 1998. Metabolic precursors for milk synthesis. In: The Lactating Sow. Chapter 4. (Ed. M.W.A. Verstegen, P.J. Moughan, and J.W. Schrama). Wageningen University Press, The Netherlands. pp. 71-93.

Boyd, R.D., K.J. Touchette, G.C. Castro, M.E. Johnston, K.U. Lee, and In K. Han. 2000. Recent advances in amino acid and energy nutrition of prolific sows - review. J. Anim. Sci. 13: 1638-1652.

Brendemuhl, J.H., A.J. Lewis, and E.R. Peo, Jr. 1989. Influence of energy and protein intake during lactation on body composition of primiparous sows. J. Anim. Sci. 67:1478-1488.

Canolty, N.L., and Nasset, E.S. 1975. Intestinal absorption of free and protein-bound dietary methionine in the rat. J. Nutr. 105:867-877.

Carter, S.D., G.M. Hill, D.C. Mahan, J.L. Nelssen, B.T. Richert, and G.C. Shurson. 2000. Effects of dietary valine concentration on lactational performance of sows nursing large litters. J. Anim. Sci. 78:2879-2884.

Cervantes R, M., G.L. Cromwell, and T.S. Stahly. 1995. Synthetic amino acid supplementation in the low protein grain sorghum-soybean meal diet for pigs. Cuban J. Agric. Sci. 29:197-208.

Close, W.H., J. Noblet, and R.P. Heavens. 1985. Studies on the energy metabolism of the pregnant sow. 2. The partition and utilization of metabolizable energy intake in pregnant and non-pregnant animals. Br. J. Nutr. 53:267-279.

Clowes, E.J. 2001. Lactational protein loss and sow performance. Ph.D. Thesis. University of Alberta, Edmonton, AB.

Cooper, D.R., J.F. Patience, R.T. Zijlstra, M. Rademacher. 2001. Effect of energy and lysine intake in gestation on sow performance. J. Anim. Sci. 79:2367-2377.

Corley, J.R., and R.A. Easter. 1980. Reproductive performance and nitrogen metabolism of gilts and sows fed amino acid supplemented corn diets during gestation. J. Anim. Sci. 51(Suppl. 1):191-192. (Abstr.).

Corley, J.R., M.W. Esch, J.M. Bahr, and R.A. Easter. 1983. Amino acid supplementation of low-protein diets for swine: effects of gestation treatment on reproductive performance of gilts and sows. J. Anim. Sci. 56:108-117.

Cuaron, J.A., R.P. Chapple, and R.A. Easter. 1984. Effect of lysine and threonine supplementation of sorghum gestation diets on nitrogen balance and plasma constituents in first-litter gilts. J. Anim. Sci. 58:631-637.

Dourmad, J.Y., M. Etienne, and J. Noblet. 1996. Reconstitution of body reserves in multiparous sows during pregnancy: Effect of energy intake during pregnancy and mobilization during the previous lactation. J. Anim. Sci. 74: 2211-2219.

Dourmad, J.Y., and M. Etienne. 2002. Dietary lysine and threonine requirements of the pregnant sow estimated by nitrogen balance. J. Anim. Sci. 80:2144-2150.

Drummond, J.G., S.E. Curtis, J. Simon, and H.W. Norton. 1980. Effects of aerial ammonia on growth and health of young pigs. J. Anim. Sci. 50:1085-1091.

Easter, R.A., and S.W. Kim. 1998. Recent advances in the nutrition of the high producing sow – review-. Am. J. Anim. Sci. 11 (6): 769-773.

Edwards A.C., and R.G. Campbell. 1993. Energy-protein interactions in pigs. In: Recent Developments in Pig Nutrition 2. Ed. DJA Cole. Wittlaresign, PC Garnsworthy. pp. 30-46.

Eissen, J.J., E. Kanis, and B. Kemp. 2000. Sow factors affecting voluntary feed intake during lactation. Livestock Prod. Sci. 64: 147-165.

Everts, H., and R.A. Dekker. 1994. Effect on nitrogen supply on the retention and excretion of nitrogen and on energy metabolism of pregnant sows. Anim. Prod. 59: 293-301.

Everts, H., and R.A. Dekker. 1995. Effect of protein supply during pregnancy and lactation on body composition of sows during three reproductive cycles. Livestock Prod. Sci. 43:137-147.

Falaschini, A.F., L.A. Volpelli, and M.F. Trombetta. 1994. Effects of protein and/or amino-acid levels on reproductive performance and metabolic profile of lactating sows. Ann. Zootech. 43:151-161.

Fuller, M.F., R. McWilliam, and T.C. Wang. 1987. The amino acid requirement of pigs for maintenance and for growth. Anim. Prod. 44:476-477 (Abstr.)

Fuller, M.F., P.R. Beckett, and T.C. Wang. 1989. Ideal Protein: The concept and its application in swine diets. Proc. Of the 10th Western Nutr. Conf., Winnipeg, Canada.

Fuller, M.F., R. McWilliam, T.C. Wang, and L.R. Giles. 1989. The optimum dietary amino acid pattern for growing pigs 2. Requirements for maintenance and for tissue protein accretion. Br. J. Nutr. 62: 255-267.

Gatel, F., and F. Grosjean. 1992. Effect of protein content of the diet on nitrogen excretion by pigs. Livestock Prod. Sci. 31: 109-120.

George, S.A., R. Elliot, and E.S. Batterham. 1988. Effect of carbohydrate source and feeding frequency on protein and energy retention by the growing pig. Proc. Nutr. Soc. Aust. 13:118.

Gomez, R.S., A.J. Lewis, P.S. Miller, and H.-Y. Chen. 2002. Growth performance, diet apparent digestibility, and plasma metabolite concentrations of barrows fed corn-soybean meal diets or low-protein, amino acid-supplemented diets at different feeding levels. J. Anim. Sci. 80:644-653.

Han, In K., and J.H. Lee. 2000. The role of synthetic amino acids in monogastric animal production – review -. Asian-Aus. J. Anim. Sci. 13 (4): 543-560.

Han, In K., J.H. Lee, X.S. Piao, and Defa Li. 2001. Feeding and management system to reduce environmental pollution in swine production – review. Asian–Aust. J. Anim. Sci. 14(3): 432-444.

Heger. J., S. Mengesha, J. Blaha, and F. Koch. 1997. Estimation of minimum crude protein level in diets for high-lean growth pigs. Agribiol. Res. 50:64-77.

Honeyman, M.S. 1993. Environment-friendly swine feed formulation to reduce nitrogen and phosphorous excretion. Am. J. Alternative Agriculture. 8:128-132.

Hsieh, W.M., and S.H. Chiang. 1994. Effects of the supplementation of low-protein diets with amino acids on growth performance and the excretion of nitrogen and organic matter in growing pigs. Journal of the Chinese Society of Animal Science. 23:109-120.

Hurley, W.L., H. Wang, J.M. Bryson, and D.B. Shennan. 2000. Lysine uptake by mammary gland tissue from lactating sows. J. Anim. Sci. 78:391-395.

Illingworth, P.J., R.T. Jung, P.W. Howie, and T.E. Isles. 1987. Reduction in postprandial energy expenditure during pregnancy. Br. J. Med. Jun 20; 294:1573-1576.

Jamroz, D., and J. Kubizna. 2001. Reducing the environment pollution through modification of performed animals nutrition. Krmiva. 4:195-209.

Jin, C.F., J.H. Kim, In K. Han, and S.H. Bae. 1998. Effects of supplemental synthetic amino acids to the low protein diets on the performance of growing pigs. A.J.A.S. 11:1-7.

Johnston. L.J. M. Ellis, G.W. Libal, V.B. Mayrose, W.C. Weldon, and NRC-89 Committee on Swine Management. 1999. Effect of room temperature and dietary amino acid concentration on performance of lactating sows. J. Anim. Sci. 77:1638-1644.

Jones, D.B., and T.S. Stahly. 1999. Impact of amino acid nutrition during lactation on body nutrient mobilization and milk nutrient output in primiparous sows. J. Anim. Sci. 77:1513-1522.

Jongbloed A.W., and N.P. Lenis. 1992. Alteration of nutrition as a means to reduce environmental pollution by pigs. Livestock Prod. Sci. 31: 75-94.

Just, A. 1982. The net energy value of crude (catabolized) protein for growth in pigs. Livestock Prod. Sci. 9:349-360.

Just, A. 1984. Nutritional manipulation and interpretation of body compositional differences in growing swine. J. Anim. Sci. 58:740-752.

Kerr, B.J. 1997. Amino acid nutrition of lactating sows. Biokyowa Technical Review-10. Biokyowa Inc.

Kerr, B.J., and R.A. Easter. 1986. The effect of meal frequency and lysine supplementation on nitrogen retention of gravid gilts. J. Anim. Sci. 63 (Suppl. 1):272 (Abstr.).

Kerr, B.J. and R.A. Easter. 1995. Effect of feeding reduced protein, amino acid-supplemented diets on nitrogen and energy balance in grower pigs. J. Anim. Sci. 73:3000-3008.

Kerr, B.J., F.K. McKeith, and R.A. Easter. 1995. Effect on performance and carcass characteristics of nursery to finisher pigs fed reduced crude protein, amino acid-supplemented diets. J. Anim. Sci. 73:433-440.

Kim, S.W., W.L. Hurley, I.K. Han, and R.A. Easter. 1999. Changes in tissue composition associated with mammary gland growth during lactation in sows. J. Anim. Sci. 77:2510-2516.

Kim, S.W., D.H. Baker, and R.A. Easter. 2001. Dynamic ideal protein and limiting amino acids for lactating sows: The impact of amino acid mobilization. J. Anim. Sci. 79:2356-2366.

King, R.H., and I.H. Williams. 1984. The effect of nutrition on the reproductive performance of first-litter sows. 2. Protein and energy intakes during lactation. Anim. Prod. 38:249-256.

King, R.H., M.S. Toner, and H. Dove. 1989. Pattern of milk production in sows. In: Manipulating Pig Production II. (Ed. J.L. Barnett and D.P. Hennessy). Australasian Pig Sci. Assoc., Werribee, Austrailia. p. 98.

King, R.H., and W.G. Brown. 1993. Interrelationships between dietary protein level, energy intake, and nitrogen retention in pregnant gilts. J. Anim. Sci. 71:2450-2456.

King, R.H., M.S. Toner, H. Dove, C.S. Atwood, and W.G. Brown. 1993. The response of first-litter sows to dietary protein level during lactation. J. Anim. Sci. 71:2457-2463.

Kirkhorn, S.R., and V.F. Garry. 2000. Agricultural lung diseases. Environ. Health Perspec. 108 (Suppl. 4):705-712.

Knabe, D.A., J.H. Brendemuhl, L.I. Chiba, and C.R. Dove. 1996. Supplemental lysine for sows nursing large litters. J. Anim. Sci. 74:1635-1640.

Koch. F. 1996. Ideal protein for pigs and poultry. Krmiva. 38:25-32.

Kusina, J., J.E. Pettigrew. A.F. Sower, M.R. Hathaway, M.E. White, and B.A. Crooker. 1999a. Effect of protein intake during gestation on mammary development of primiparous sows. J. Anim. Sci. 77:925-930.

Kusina, J., J.E. Pettigrew. A.F. Sower, M.E. White, B.A. Crooker, and M.R. Hathaway. 1999b. Effect of protein intake during gestation and lactation on the lactational performance of primiparous sows. J. Anim. Sci. 77:931-941.

Le Bellego, L., J. van Milgen, S. Dubois, and J. Noblet. 2001. Energy utilization of low-protein diets in growing pigs. J. Anim. Sci. 79:1259-1271.

Le Bellego, L., J. van Milgen, and J. Noblet. 2002. Effect of high temperature and low-protein diets on the performance of growing-finishing pigs. J. Anim. Sci. 80:691-701.

Lee, J.H., J.H. Kim, J.D. Kim, S.W. Kim, and In K. Han. 2001. Effects of low crude protein diets supplemented with synthetic amino acids on performance, nutrient utilization and carcass characteristics in finishing pigs reared using a phase feeding regimen. Asian-Aust. J. Anim. Sci. 14:655-667.

Lenis, N.P. 1989. Lower nitrogen excretion in pig husbandry by feeding: current and future possibilities. Neth. J. Agric. Sci. 37:61-70.

Lenis, N.P. and A.W. Jongbloed. 1999. New technologies in low pollution diet: diet manipulation and use of synthetic amino acids, phytase and phase feeding for reduction of nitrogen and phosphorous excretion and ammonia emission – review-. Asian-Aus. J. Anim. Sci. 12:305-327.

Libal, G.W., D.J. Uttecht, and C.R. Hamilton. 1997. Tryptophan needs of lactating sows fed diets supplemented with crystalline lysine. J. Anim. Sci. 75:417-422.

Mahan, D.C. 1977. Effect of feeding various gestation and lactation dietary protein sequences on long-term reproductive performance in swine. J. Anim. Sci. 45:1061-1072.

Mahan D.C., and L.T. Mangan. 1975. Evaluation of various protein sequences on the nutritional carry-over from gestation to lactation with first-litter sows. J. Nutr. 105: 1291-1298.

Mathison, G.W., J. Buchanan-Smith, S. Möhn and R.O. Ball. 1999. Feeding strategies for mitigation of greenhouse gas emissions. Consulting Report for the Agriculture and Agri-Food Round Table on Climate Change. Ottawa, Ontario.

McNamara, J.P., and J.E. Pettigrew. 2002. Protein and fat utilization in lactating sows: I. Effects on milk production and body composition. J. Anim. Sci. 80:2442-2451.

Mennenga, V.O. 1986. Lysine and tryptophan supplementation of low-protein, corn-soybean meal diets for lactating swine. M.Sc. Thesis. University of Illinois, Urbana Champaign, IL.

Misselbrook, T.H., D.R. Chadwick, B.F. Pain, and D.M. Headon. 1998. Dietary manipulation as a means of decreasing N losses and methane emissions and improving herbage N uptake following application of pig slurry to grassland. J. Agric. Sci. 130:183-191.

Möhn, S., and A. Susenbeth. 1995. Influence of dietary protein content on efficiency of energy utilization in growing pigs. Arch. Anim. Nutr. 47:361-372.

Moser, S.A., M.D. Tokach, S.S. Dritz, R.D. Goodband, J.L. Nelssen, and J.A. Loughmiller. 2000. The effects of branched-chain amino acids on sow and litter performance. J. Anim. Sci. 78:658-667.

Myer, R.O., J.H. Brendemuhl, and R.D. Barnett. 1996. Crystalline lysine and threonine supplementation of soft red winter wheat or triticale, low-protein diets for growing-finishing swine. J. Anim. Sci. 74:577-583.

Nelssen, J. 2000. New developments in sow nutrition in the USA. Lohmann Information. 24:7-12.

Noblet, J., and M. Etienne. 1986. Effect of energy level in lactating sows on yield and composition of milk and nutrient balance of piglets. J. Anim. Sci. 63:1888-1896.

Noblet, J., Y. Henry, and S. Dubois. 1987. Effect of protein and lysine levels in the diet on body gain composition and energy utilization in growing pigs. J. Anim. Sci. 65:717-726.

Noblet, J., J.Y. Dourmad and M. Etienne. 1990. Energy utilization in pregnant and lactating sows: modeling of energy requirements. J. Anim. Sci. 68:562-572.

Noblet, J., J.Y. Dourmad, M. Etienne and J. Le Dividich. 1997. Energy metabolism in pregnant sows and newborn pigs. J. Anim. Sci. 75:2708-2714.

Noblet, J., M. Etienne, and J.-Y. Dourmad. 1998. Energetic efficiency of milk production. In: The Lactating Sow. Sow (Ed. M.W.A. Verstegen, P.J. Moughan, and J.W. Schrama). Wageningen University Press, The Netherlands. pp. 113-130.

NRC. 1988. Nutrient Requirements of Swine (9th Ed.). National Academy Press. Washington, DC.

NRC. 1998. Nutrient Requirements of Swine (10th Ed.). National Academy Press. Washington, DC.

O'Grady, J.F., and T.J. Hanrahan. 1975. Influence of protein level and amino-acid supplementation of diets fed in lactation on the performance of sows and their litters. 1. Sow and litter performance. Ir. J. Agric. Sci. 14:127-135.

Partridge, I.G., A.G. Low, and D.H. Keal. 1985. A note on the effect of feeding frequency on nitrogen use in growing boars given diets with varying levels of free lysine. Anim. Prod. 40:372-377.

Pettigrew, J.E. 1993. Amino acid nutrition of gestating and lactating sows. Biokyowa Technical Review No. 5. Biokyowa Inc. Chesterfield, MO.

Pettigrew, J.E., and H. Yang. 1997. Protein nutrition of gestating sows. J. Anim. Sci. 75:2723-2730.

Prunier, A., C.A. Mejia Guadarrama, J. Mourot, and H. Quesnel. 2001. Influence of feed intake during pregnancy and lactation on fat body reserve mobilization, plasma leptin and reproductive function of primiparous lactating sows. Reprod. Nutr. Dev. 41:333-347.

Quiniou, N., S. Dubois, J. Noblet. 1995. Effect of dietary crude protein level on protein and energy balances in growing pigs: comparison of two measurement methods. Livestock Prod. Sci. 41:51-61.

Reeds, P.J., A. Cadenhead, M.F. Fuller, G.E. Lobley and J.D. McDonald. 1980. Protein turnover in growing pigs: Effects of age and food intake. Br. J. Nutr. 43:445-455.

Renaudeau, D., and J. Noblet. 2001. Effects of exposure to high ambient temperature and dietary protein level on sow milk production and performance of piglets. J. Anim. Sci. 79: 1540-1548.

Renaudeau, D., N. Quiniou, and J. Noblet. 2001. Effects of exposure to high ambient temperature and dietary protein level on performance of multiparous sows. J. Anim. Sci. 79:1240-1249.

Rerat, A.A. 1985. Intestinal absorption of end products from digestion of carbohydrates and proteins in the pig. Archiv Fur Tirernahrung. 35:461-480.

Revell, D.K., I.H. Williams, B.P. Mullan, J.L. Ranford, and R.J. Smits. 1998a. Body composition at farrowing and nutrition during lactation affect the performance of primiparous sows: I. Voluntary feed intake, weight loss, and plasma metabolites. J. Anim. Sci. 76: 1729-1737.

Revell, D.K., I.H. Williams, B.P. Mullan, J.L. Ranford, and R.J. Smits. 1998b. Body composition at farrowing and nutrition during lactation affect the performance of primiparous sows: II. Milk composition, milk yield, and pig growth. J. Anim. Sci. 76: 1738-1743.

Richert, B.T., M.D. Tokach, R.D. Goodband, J.L. Nelssen, J.E. Pettigrew, R.D. Walker, and L.J. Johnston. 1996. Valine requirement of the high-producing lactating sow. J. Anim.Sci. 74:1307-1313.

Richert, B.T., R.D. Goodband, M.D. Tokach, and J.L. Nelssen. 1997a. Increasing valine, isoleucine, and total branched-chain amino acids for lactating sows. J. Anim.Sci. 75:2117-2128.

Richert, B.T., M.D. Tokach, R.D. Goodband, J.L. Nelssen, R.G. Campbell, and S. Kershaw. 1997b. The effect of dietary lysine and valine fed during lactation on sow and litter performance. J. Anim. Sci. 75: 1853-1860.

Schoenherr, W.D. 1992. Ideal protein formulation of diets for growing-finishing pigs housed in a hot environment. J. Anim. Sci. 70 (Suppl. 1):242 (Abstr.).

Sharda, D.P., D.C. Mahan, and R.F. Wilson. 1976. Limiting amino acids in low-protein corn-soybean meal diets for growing-finishing swine. J. Anim. Sci. 42:1175-1181.

Sinclair, A.G., J.M. Shaw, S.A. Edwards, S. Hoste, and A. McCartney. 1999. The effect of dietary protein level on milk yield and composition and piglet growth and composition of the Meishan synthetic and European White breeds of sow. Anim. Sci. 68:701-708.

Sinclair, A.G., V.C. Bland, and S.A. Edwards. 2001. The influence of gestation feeding strategy on body composition of gilts at farrowing and response to dietary protein in a modified lactation. J. Anim. Sci. 79:2397-2405.

Stahly, T.S., G.L. Cromwell, and H.J. Monegue. 1992. Milk yield responses of sows nursing large litters to dietary amino acid levels. J. Anim. Sci. 70 (Suppl 1):238 (Abstr.).

Stein, H.H., S. Aref, and R.A. Easter. 1999. Comparative protein and amino acid digestibilities in growing pigs and sows. J. Anim. Sci. 77:1169-1179.

Sutton, A.L., K.B. Kephart, M.W.A. Verstegen, T.T. Canh, and P.J. Hobbs. 1999. Potential for reduction of odorous compounds in swine manure through diet modification. J. Anim. Sci. 77: 430-439.

Tachibana, F., and H. Ubagai. 1997. Effect of reducing crude protein and energy content in diets with amino acid supplementation on nitrogen balance, performance and carcass characteristics in pigs. Anim. Sci. Technol. 68:640-649.

Tokach, M.D., J.E. Pettigrew, B.A. Crooker, G.D. Dial, and A.F. Sower. 1992a. Quantitative influence of lysine and energy intake on yield of milk components in the primiparous sow. J. Anim. Sci. 70: 1864-1872.

Tokach, M.D., R.D. Goodband, J.L. Nelssen, J.L. Laurin, and J.A. Hansen. 1992b. The effects of an ideal protein lactation diet on sow and litter performance. J. Anim. Sci. 70 (Suppl. 1):69 (Abstr.).

Touchette, K.J., G.L. Allee, M.D. Newcomb, and R.D. Boyd. 1998. The lysine requirement of lactating primiparous sows. J. Anim.Sci. 76:1091-1097.

Trombetta, M.F., E. Codoni, S. Mattii, and A. Falaschini. 2001. Low-protein diets for lactating sows: digestive utilisation, performance parameters and environmental impact. Pig News and Information 22:119N-124N.

Trottier, N.L., C.F. Shipley, and R.A. Easter. 1994. Arteriovenous differences for amino acids, urea nitrogen, ammonia and glucose across the mammary gland of the sow. J. Anim. Sci. 72 (Suppl 1):332 (Abstr.).

Trottier, N.L. 1997. Nutritional control of amino acid supply to the mammary gland during lactation in the pig. Proc. Nutr. Soc. 56:581-591.

Trottier, N.L., C.F. Shipley, and R.A. Easter. 1997. Plasma amino acid uptake by the mammary gland of the lactating sow. J. Anim. Sci. 75:1266-1278.

Tuitoek, K., L.G. Young, C.F.M. de Lange, and B.J. Kerr. 1997a. The effect of reducing excess dietary amino acids on growing-finishing pig performance: an evaluation of the ideal protein concept. J. Anim. Sci. 75:1575-1583.

Tuitoek, K., L.G. Young, C.F.M. de Lange, and B.J. Kerr. 1997b. Body composition and protein and fat accretion in various body components in growing gilts fed diets with different protein levels but estimated to contain similar levels of ideal protein. J. Anim. Sci. 75:1584-1590.

Uttecht, D.J., C.R. Hamilton, E.M. Weaver, and G.W. Libal. 1991. Interaction between dietary levels of neutral amino acids and tryptophan fed to 10-kg pigs. J. Anim. Sci. 69 (Suppl. 1):364 (Abstr.).

van der Peet-Schwering, C.M.C., and L.A. den Hartog. 2000. Manipulation of pig diets to minimize the environmental impact of pig production in the Netherlands. Pig News and Information. 21:54N-58N.

Ward, T.L. and L.L. Southern. 1995. Sorghum amino acid-supplemented diets for the 50 to 100-kilogram pig. J. Anim. Sci. 73:1746-1753.

Wilkinson, R., D.J.A. Cole, and D. Lewis. 1984. Amino acid nutrition of the lactating sow: limitation by indispensable amino acids. Anim. Prod. 38:263-270.

Willis, G.M., and C.V. Maxwell. 1984. Influence of protein intake, energy intake and stage of gestation on growth, reproductive performance, nitrogen balance and carcass composition in gestating gilts. J. Anim. Sci. 58:647-656.

Wu, G., and D.A. Knabe. 1994. Free and protein-bound amino acids in sow's colostrum and milk. J. Nutr. 124 (3): 415-424.

Yang, H., J.E. Pettigrew, L.J. Johnston, G.C. Shurson, and R.D. Walker. 2000a. Lactational and subsequent reproductive responses of lactating sows to dietary lysine (protein) concentration. J. Anim.Sci. 78:348-357.

Yang, H., J.E. Pettigrew, L.J. Johnston, G.C. Shurson, J.E. Wheaton, M.E. White, Y. Koketsu, A.F. Sower, and J.A. Rathmacher. 2000b. Effects of dietary lysine intake during lactation on blood metabolites, hormones, and reproductive performance in primiparous sows. J. Anim. Sci. 78:1001-1009.

3.0 HYPOTHESIS & OBJECTIVES

In order to meet the requirement for the first limiting amino acid, lysine, diets provide large excesses of other amino acids, relative to the animals' requirements (Johnston et al, 1999). These excess amino acids are not used for metabolic processes, but are catabolized, and their nitrogen excreted in the urine, mainly as urea. Increasing public concern that the swine industry is depositing excessive quantities of nitrogen into the environment, potentially contaminating soil and water supplies, has forced the re-evaluation of current feeding practices. Experimental evidence indicates that the environmental impact of swine production can be reduced through diet modification (Lenis, 1989; Gatel and Grosjean, 1992; Jongbloed and Lenis, 1992). Feeding low protein diets, supplemented with limiting amino acids, to growing pigs reduces nitrogen excretion, however, animal performance has been variable. Although adult sows contribute a substantial portion of the nitrogen excreted by the swine population, information on the effects of feeding low protein, amino acid supplemented diets to sows, on their performance and nitrogen excretion, is limited preventing the use of these diets in commercial situations.

3.1 Hypotheses

1) Properly formulated, low protein, amino acid supplemented diets will support performance equal to that of sows fed a conventional intact protein diet.

2) Sows fed low protein diets with adequate amino acid supplementation will exhibit similar maternal gains (and losses) as sows fed conventional diets, and the composition of these weight changes will be similar.

3) Feeding low protein, amino acid supplemented diets in one parity will not influence performance in the subsequent parity.

4) Sows fed low protein diets with adequate amino acid supplementation will have lower urinary nitrogen excretion, and lower energy expenditure than sows fed conventional diets.

5) Low protein, amino acid supplemented diets will be economically competitive with conventional, intact protein diets for sows.

3.2 Objectives

The main objective of this experiment was to determine the effect feeding of low protein diets, supplemented with synthetic lysine and threonine in both gestation and lactation for two consecutive parities on a variety of production characteristics. To provide a comprehensive evaluation of the effect of low protein, amino acid-supplemented diets on the sow, we addressed several objectives.

1) To determine the effect of feeding low protein-amino acid adequate diets on sow performance, feed intake, litter characteristics (numbers born and weaned, piglet weights) and reproductive adequacy (wean to estrus interval, percentage return to service, conception rate, farrowing rate) were monitored and recorded.

2) To determine whether feeding low protein, amino acid supplemented diets in one parity affects performance in the subsequent parity, performance data was acquired for two consecutive parities.

3) To determine the effect of reduced protein diets on the changes in body weight and the composition of weight gain/loss, sows were repeatedly weighed and ultrasonically measured for backfat thickness over time. Additionally, body composition was determined by isotopic tracer (deuterium oxide) dilution in a subsample of animals.

4) To determine the effect of low protein, amino acid supplemented diets on sow milk production and composition, sows and piglets underwent weigh-suckle-weigh, and samples of milk were obtained in a subsample of animals.

5) To determine the effect of decreased dietary crude protein, with adequate amino acid supplementation on diet digestibility and urinary nitrogen excretion in gestating and lactating

sows, samples of urine and feces were obtained from a subsample of sows. Diet digestibility was indirectly determined by adding an indigestible marker to the feed, and urinary nitrogen excretion calculated using the ratio of nitrogen to creatinine in the urine. Additionally, plasma amino acids were examined during gestation and lactation of the second parity to determine other metabolic consequences of feeding low protein diets.

6) To determine the effect of low protein, amino acid supplemented diets on energy metabolism of producing sows, heat production was determined by indirect calorimetry during gestation and lactation in a subsample of sows.

7) To determine the economic viability of feeding low protein, amino acid supplemented diets in gestation and lactation, least cost diets were formulated, and margin over feed cost calculated for each diet treatment for the entire experiment.

4.0 INTRODUCTION

Manipulating swine diets to reduce the environmental impact of pig production by decreasing crude protein content and supplementing with limiting amino acids is not a novel concept. The ability of low-protein, amino acid supplemented diets fed to growing and finishing pigs to reduce nitrogen excretion has been well documented. However, there is a scarcity of information as to the suitability of such diets for producing sows, even though they are responsible for a sizable portion of the nitrogen excreted in swine production. Due to the limited knowledge of the suitability of low protein, amino acid supplemented diets for sows and the physiological dissimilarities between growing pigs and producing sows, more research to examine the effect of low protein diets during all facets of the sow's productive life is required if these diets are to be utilized commercially. Questions that need to be addressed include whether these low protein diets:

1) influence sow performance characteristics

2) affect body composition and growth of sows

3) alter milk production and composition

4) decrease nitrogen excretion

5) fed in one parity affects performance in the subsequent parity

6) affect heat production, similar to evidence from grower pig studies

7) can be fed economically (i.e. margin over feed cost) to producing sows

To increase the scientific knowledge in these areas, we developed an experiment to examine these questions.

4.1 MATERIALS AND METHODS

The University of Alberta's Faculty of Agriculture, Forestry and Home Economics Animal Policy and Welfare Committee approved all procedures used in this study.

4.1.1 Experimental Design

Second parity sows were allocated to either a conventional or a low protein, amino acid supplemented diet on the basis of body condition at breeding and performance during the previous lactation. Performance of all sows was followed for two complete reproductive cycles. A subsample of sows underwent intensive studies, including energy expenditure, milk production and composition, nitrogen excretion, diet digestibility and body composition measures. The experiment was designed as a multi-way factorial comparing two diet regimens (high protein and low protein) in two physiological states (gestation and lactation) with two time points per state (early and late stages) during two parities (2 and 3).

4.1.1.1 Sow Selection

Second parity Landrace X Large White sows (n= 80, 164.3 kg ± 2.1 kg) from the University of Alberta's Swine Research Unit were selected in 11 groups from October 2000 through February 2001. Sow selection was restricted by routine operation at the SRU, which weans up to 12 Genex F1 sows every three out of four weeks. Sows were selected in pairs immediately after breeding according to similar means in body weight, backfat depth and number of piglets born in the previous lactation and allotted to either a commercial high protein diet (HP), or a low-protein diet supplemented with synthetic amino acids (LP). Sow selection continued until 40 sows per treatment had been confirmed pregnant. Any sow initially selected, then found to be not pregnant, was removed from the experiment. Once pregnancy was confirmed, sows were maintained on their allotted dietary regimen for two consecutive parities to determine if treatment in one parity affected performance in the subsequent parity. One pair of sows from each breeding group (n= 22) was randomly selected to undergo intensive measurements including determination of energy expenditure by indirect calorimetry, weigh-suckle-weigh (WSW) to determine milk production and milk composition, and collection of spot samples of urine and feces for determination of nitrogen excretion and diet digestibility at

early and late gestation and early and late lactation of both parities. The intensive sows from the last six breeding groups (n=12) also underwent determination of body composition by deuterium oxide dilution at the same time points as the other intensive measurements during their second parity.

4.1.1.2 Housing and Management

The majority of the gestating sows were housed as breeding groups in open pens with individual stalls for feeding. Due to lack of space availability, some sows were housed in a second barn in standard gestation crates, however, dietary treatment was equally represented within each barn. The effect of barn could not be tested, because sows moved indiscriminately between the two barns, as management practices dictated. Temperature in both barns was maintained as close to 18 to 20°C as possible. During winter months, supplemental heat was provided to one gestation barn via gas heaters to help maintain room temperature similar to the other barn. On day 109 of gestation, sows were moved into individual farrowing crates and switched to lactation feed. Two separate barns were used to house lactating sows, however, all sows in a lactation group were housed together.

4.1.2 Diets and Feeding

4.1.2.1 Diet Composition

Diets for gestation and lactation were formulated using feedstuffs commonly available in Western Canada. The high protein diets used during the experiment were the standard gestation and lactation diets fed at the University of Alberta's Swine Research Unit. These diets were formulated at Consultant Feeds in Calmar, Alberta, specifically for the genetic stock housed at the Swine Unit. The low protein diets were formulated to be similar to the commercial diets in all respects except amino acid content. Nutrient composition of the feedstuffs utilized, for the purpose of formulation, was taken as the NRC (1998) nutrient composition values (Tables 11-1,11-2.11-4,11-6,11-8; NRC, 1998). We used the value of

0.096% available tryptophan in barley, given by Degussa Feed Additives (1996), rather than the value for two-row barley in NRC, which appeared lower than observed Canadian barley values. Samples of each batch of feed were obtained from the bins to allow for determination of dry matter (DM), crude protein (CP), ether extract (fat), neutral detergent fiber (NDF), ash and gross energy content. Ingredients and diets were analysed at the end of the experiment, rather than before initiation of the study, because the study was conducted over a period of almost fourteen months and required approximately 200 tonnes of feed. We could not buy and hold the quantity of ingredients necessary to make all the feed for the entire period. Therefore, we were required to live with the natural variation that occurred in the ingredient supply of two crop years.

Gestation

The high protein gestation diet (Table 4.1.1), formulated by Consultant Feeds, was used as a reference for appropriate nutrient levels for formulation of the low protein gestation diet (Table 4.1.1). The high protein diet used by the Swine Unit consisted mainly of wheat, barley and soybean meal, with canola meal as a secondary protein source (Table 4.1.1). Based on the levels of metabolizable energy, CP, minerals (Table 4.1.1) and amino acids (Table 4.1.2) provided by the reference diet, we formulated the low protein diet to be approximately 20% lower in crude protein, and iso-energetic to the high protein diet. Amino acid content of the diets (Table 4.1.2) was calculated on a true ileal digestible basis. Crystalline lysine and threonine were included in the low protein diet to return these amino acids to the levels found in the high protein diet. The lysine content of the high protein diet was slightly higher than the stated NRC requirement for a 125 kg sow (Table 4.1.2), therefore when formulating the low protein diet, the balance of the other indispensable amino acids required was recalculated to account for the increase in dietary lysine provided, according to the ideal protein concept. The concentrations of all indispensable amino acids were monitored during diet formulation to ensure that the amino acid content of the diet met or exceeded the NRC (1988)

recommendations (Table 4.1.2). Additionally, dietary fatty acid content was monitored, to ensure that the NRC (1998) recommendation was met.

Table 4.1.1 Gestation diet composition

Ingredient, g/kg	High Protein	Low Protein
Wheat	120	248
Barley	700	700.5
Soybean meal	65	5
Canola meal	65	0
Tallow	10	0
L-Lysine HCl	0	2.8
L-Threonine	0	1.2
Breeder premix a	40	40
Dicalcium phosphate	0	2.5
Chromic oxide	2.5	2.5
Composition (calculated)		
ME, MJ/kg	12.06	12.06
CP, g/kg	147.6	119.8
Minerals (calculated)		
Ca, g/kg	9.7	9.7
Available P, g/kg	4.4	4.8
Composition (analysed)		
DE, MJ/kg	14.7	13.8
DM, g/kg	898.0	894.3
CP, g/kg	162.5	135.2
Fat, g/kg	27.2	13.9
NDF, g/kg	159.5	155.2
Ash, g/kg	73.8	67.7

a) Provided per kilogram of the diet: Ca, 8.6g; P, 3.4g; Na, 1.9g; Mg, 0.4g; S, 80mg; Fe, 281 mg; Zn, 139 mg; Mn, 64 mg; Cu, 24 mg; Co, 0.08 mg; I, 0.4 mg; Se, 0.3 mg; vitamin A, 12,000 IU; vitamin D, 1400 IU; vitamin E, 62 IU; biotin, 0.6 mg; riboflavin, 7 mg; pantothenic acid, 25 mg; niacin, 38 mg.

Table 4.1.2 Calculated true ileal digestible amino content of the gestation diets

AA (g/kg)	High protein	Low Protein	NRC [a]
Arginine	7.1	4.9	0.4
Cystine	2.9	2.4	1.9
Histidine	3.1	2.3	1.7
Isoleucine	4.7	3.4	2.9
Leucine	8.9	6.8	4.8
Lysine	**5.3**	**5.3**	5.0
Methionine	2.2	1.8	1.4
Phenylalanine	6.1	5.0	2.9
Threonine	**4.1**	**4.1**	3.7
Tryptophan	1.4	1.1	1.0
Tyrosine	3.8	2.7	1.9
Valine	5.9	4.7	3.6

a) true ileal digestible amino acid requirements for a 125 kg sow gaining 55 kg during gestation with 11 piglets (NRC, 1998)

Lactation

Lactation diets (Table 4.1.3) were formulated in a similar manner as the gestation diets, using the high protein lactation diet as a reference. The calculated true ileal digestible lysine content of the high protein diet was 0.79%, which matches the NRC recommendations for a 175 kg sow, not losing weight, nursing piglets gaining 200 g/d. Therefore the ideal amino acid profile for this diet was used to formulate the low protein diet. Both diets consisted mainly of wheat, barley and soybean meal (Table 4.1.3). In order to achieve 15 to 20% decease in crude protein content, soybean meal was decreased extensively in the low protein diet. Wheat and barley are low in the branched-chain amino acids (valine, isoleucine, and leucine) as compared to soybean meal. To complement the amino acid pattern of wheat and barley, and ensure that the requirements for all amino acids were met, blood meal was included in the diet at a rate of 2.3%. Blood meal has a relatively high content of valine, leucine, histidine and lysine. Because the quality of blood meal is highly dependent on a number of factors, to minimize variation in amino acid content, a single batch of bloodmeal was acquired and used for the entire experiment. As with the gestation diet, crystalline lysine and threonine were added to the low protein diet to return these two amino acids to the level found in the high protein diet. Similarly, we ensured that concentrations of all indispensable amino acids in the low protein diet met or exceeded NRC (1998) recommendations (Table 4.1.4). Additionally, adequate intake of essential fatty acids was ensured in the low protein.

Table 4.1.3 Lactation diet composition

Ingredient, g/kg	High protein	Low protein
Wheat	510	894.1
Barley	200	0
Soybean meal	225	28
Tallow	25	8
L-lysine HCl	0	3.6
L-threonine	0	1.3
Breeder premix[a]	40	40
Dicalcium phosphate	0	2
Bloodmeal	0	23
Chromic oxide	2.5	2.5
Composition (calculated)		
ME, MJ/kg	13.17	13.18
CP, g/kg	193.1	163.1
Minerals (calculated)		
Ca, g/kg	9.7	9.7
Available P, g/kg	4.8	5.2
Composition (analysed)		
DE, MJ/kg	15.2	14.6
DM, g/kg	907.7	899.7
CP, g/kg	210.9	182.2
Fat, g/kg	42.4	22.9
NDF, g/kg	134.3	162.6
Ash, g/kg	71.6	65.4

a) Provided per kilogram of the diet: Ca, 8.6g; P, 3.4g; Na, 1.9g; Mg, 0.4g; S, 80mg; Fe, 281 mg; Zn, 139 mg; Mn, 64 mg; Cu, 24 mg; Co, 0.08 mg; I, 0.4 mg; Se, 0.3 mg; vitamin A, 12,000 IU; vitamin D, 1400 IU; vitamin E, 62 IU; biotin, 0.6 mg riboflavin, 7 mg; pantothenic acid, 25 mg; niacin, 38 mg.

Table 4.1.4 Calculated true ileal digestible amino acid content of the lactation diets

AA (g/kg)	High Protein	Low Protein	NRC [a]
Arginine	10.7	6.9	4.4
Cystine	3.2	2.8	1.8
Histidine	4.3	4.1	3.2
Isoleucine	6.7	4.4	4.4
Leucine	12.3	10.5	9.0
Lysine	**7.9**	**7.9**	7.9
Methionine	2.6	2.2	2.1
Phenylalanine	8.4	7.2	4.3
Threonine	**5.6**	**5.6**	4.9
Tryptophan	2.1	1.8	1.4
Tyrosine	5.7	4.2	4.6
Valine	7.5	6.7	6.7

a) true ileal digestible amino acid requirements for a 175 kg sow, losing 0 kg body weight, nursing piglets gaining 200 g /day (NRC, 1998)

4.1.2.2 Feeding Regimen

Gestation

During gestation, sows were fed once daily in the morning. Sows received 2.0 to 2.5 kg during parity two and 2.0 to 3.0 kg during parity three. Daily feed allowance was calculated based on weight and backfat depth at breeding, to achieve sufficient body reserves for the following lactation (Aherne and Foxcroft, 2000). Individual animal intake was recorded daily. Any feed refusals (orts) were weighed daily and subtracted from that animals' recorded intake. Temperature inside the barns was recorded daily. If the overnight temperature dropped below 18°C, feed allowance of all sows, for the following day, was increased by 50 g for each degree drop. Feed allowance was re-evaluated at early gestation (day 35 to 45) and late gestation (day 95 to 105), based on body weight and backfat at that time and, if necessary, readjusted to meet the target backfat depth of 20 mm at farrowing. This change was recorded on the feed intake sheets, to monitor the number of animals receiving this adjustment. Water was available ad libitum via nipple drinkers.

Lactation

Sows were moved into farrowing crates on day 109 of gestation and switched to 3.0 kg of lactation feed per day until farrowing. Feed refusals (orts) were weighed daily. After farrowing, feed offered was increased by 0.5 kg per day until sows were eating 5 kg and then was increased by 1 kg per day until maximum feed intake was reached. If a feed refusal was greater than 0.5 kg, no feed increase was given for the next day. Feed was offered once daily in the morning until farrowing and then three times daily (0700, 1200, 1530) ensuring that feed was available ad libitum to the sow. Water was provided ad libitum to the sows and piglets via two nipple drinkers in the pen.

4.1.3 Production Measurements

4.1.3.1 Weighing and Measurement of Backfat Depth

To evaluate body weight and composition changes, all sows were weighed and backfat depth measured at specific intervals during the experiment. Gestating sows were weighed at breeding, early (day 35 to 45) and late gestation (day 95 to 105), and then at approximately day 109 of gestation on a scale (Accurate Scale Industries, Ltd., Edmonton, Alberta) with a digital readout head capable of reading to the nearest kilogram (DF 2000, Massload Technologies, Saskatoon, SK). Backfat depth was measured at the same time using an ultrasonic probe at the last rib, 65 mm from the midline on both sides; P2 (Scanoprobe, Scanco Inc., Ithaca, NY). Backfat thickness was determined to be the average of the two sides. Lactating sows were weighed and backfat depth measured within 48 hours of farrowing and at weaning.

4.1.3.2 Estrus Detection and Measurement of Reproductive Adequacy

Sows were checked for estrus according to standard procedures at the swine research unit. Pregnancy was confirmed using real-time ultrasound (Ultrascan 45, Alliance Medical Inc., Montreal, PQ) by 30 days post breeding. All animals confirmed pregnant were maintained on their experimental diets for the remainder of the trial. Wean to estrus interval for each sow was determined by calculating the number of days from weaning until standing heat was observed. Sows that returned to estrus but did not conceive immediately after their second parity weaning were rebred at their 21 or 42 day post weaning estrus following standard procedures and maintained on the experiment. As well, any sows that did not return immediately to estrus after their second parity weaning were maintained on the experimental protocol until 42 days post weaning and then culled or rebred at three or six weeks post weaning if estrus was detected. Production data from second parity sows that did not return to estrus after weaning, and were subsequently culled, was retained for analysis. From the production data, the percent of animals returning to service after weaning, conception rate of sows bred

after weaning, and farrowing rate of bred sows was calculated. These measures were used as indices of reproductive performance.

4.1.3.3 Litter Characteristics

Litter characteristics were obtained from the Swine Unit's PigWIN® records (FarmPro Systems Ltd., Te Awamutu, New Zealand). Number of piglets born, individual piglet weights and piglet identification were recorded within 24 hours of farrowing. All piglets were given 1 cc iron dextran, 1 cc Penicillin G, and had their teeth and tails clipped within two days of birth. Litter size was standardized to a minimum of eight piglets, according to normal management procedures. Due to the low number of sows in each farrowing group, piglets were fostered irrespective of dietary treatment, within 48 hours after birth. Any cross fostering events were recorded. Male piglets were castrated by 12 days of age. Litter size and individual piglet weights were recorded at weaning. Piglets had no access creep feed during lactation. Water was available to the piglets from a nipple drinker. Some piglets were removed from the sows for other research purposes within two days of birth. These piglets were regarded as partial weans in the Swine unit's records, and their weights were included in the weaning weight of the litter. Litter sizes and weights were recalculated once piglets had been removed, and this information recorded for the purposes of this experiment as " initial piglets nursed". Additionally, several ten-day old piglets were removed for a separate experiment. When possible, these piglets were replaced with piglets of similar size. Weights of all removed piglets were recorded and included in the overall weaning weights (part weaned plus weaned). In order to calculate piglet growth, final weights of nursing piglets that remained on the sow until weaning at approximately twenty-one days were recorded separately as "final piglets nursed".

4.1.4 Intensive Measurements

4.1.4.1 Respiration Procedures

Our laboratory is equipped with an open-circuit respiration system suitable for swine, and because carbon/ nitrogen balance was not possible during this experiment, oxygen consumption, carbon dioxide excretion and heat expenditure were determined by indirect calorimetry.

Early and late pregnancy (gestation 2 and 3)

Sows were housed overnight in 1.5 m X 2.1 m pens at the University of Alberta Metabolic Unit and moved the following morning into open circuit respiration chambers consisting of a standard size farrowing crate completely surrounded by a plexiglass and plastic box (rubber flooring over metal base) (Figure 4.1.1). A drinker inside the box, hooked up to an external water line and a capped plastic tube leading to the feeder provided external means of offering food and water to the animal. Access to the animal was possible via a removable plexiglass section at the top of the box. Calorimetry equipment was calibrated the morning of each respiration using gases of known composition (Praxair, Edmonton, Alberta). For calibration of the zero reading, pure nitrogen was used. The upper level of the measurement range was calibrated against a gas mixture containing 1% CO_2, 20% O_2, and 79% N_2. Measurements of these gases at steady state and room air were recorded before and after the test period. After calibration, two Gast Model 1023 pumps (Gast MFG Corp., Benton Harbor, Michigan), pulling a total of 275 L of air per minute through the box were turned on (to ensure that CO_2 concentration was maintained below 1.0%), and the respiration boxes closed, leaving openings at the back of the crate for room air to enter the box, and the tube leading to the data collection equipment. Each box was connected to individual oxygen and carbon dioxide analysers, and all analyser output routed to a single computer. Data acquisition was set to maximum rate to obtain one-minute averages of gas concentration (Data Grabber, Data Electronics, Australia).

Air was sub sampled from the main air stream using a Gast Model 0531 pump and delivered to the analysers at a rate of 0.5 L/min. To account for any differences in measurement between the sets of analysers, once the readings of respired air for each sow stabilized, the air lines from each box, in turn, were connected to both sets of oxygen and carbon dioxide analyzers for several minutes. The boxes were then reconnected to their original analysers and measurements for the day commenced. Measurements were recorded for four consecutive hours and animals were fed one quarter of their daily feed allotment every hour. Airflow, temperature and humidity inside the respiration crate were recorded every 30 minutes. Once data collection was complete for the day, animals were returned to the University of Alberta Swine Research Unit until the next respiration date.

Early and late lactation (parity 2 and 3)

Procedures for calibration were identical to that for pregnant sows. Airflow for these respirations was increased to approximately 310 L/min using a third pump to account for the extra CO_2 production from the lactating sow and her litter.

Animals were housed at the Swine Unit until one half hour before movement to the respiration chambers and returned to the Swine Unit immediately after measurements were complete. For lactation measurements, the respiration boxes were fitted with side boxes of plexiglass and metal with a rubber floor to provide a resting area for piglets. A small amount of shavings was placed in the piglet area for use as bedding, and to absorb excess moisture. The boxes were also fitted with in-floor copper cooling pipes to reduce potential sow heat stress.

Sow and litter were treated as a single entity for respiration measurements. Visual observations of nursing and piglet activity were recorded. Lactating sows tended not to eat at every hourly feeding, so feeding behaviour, at the time when it occurred, was also recorded.

In addition to the four hours of respiration with piglets, the sows were measured alone for 40 minutes while piglets were contained away from the sow. Separation of the sow and litter for this short period did not appear to cause distress to the majority of the sows.

Calculation

Heat production was calculated using the formula of Brouwer (1965)

$M\ (kJ) = 16.18 * V_{O2} + 5.02 * V_{CO2} - 5.99 * N - 2.17 * V_{CH4}$

where M is heat production, V is volume of gas in litres, and N is nitrogen excreted into urine, in grams.

Because we did not measure total nitrogen excretion or methane production, the Brouwer formula was reduced to:

$M\ (kJ) = 16.18 * V_{O2} + 5.02 * V_{CO2}$

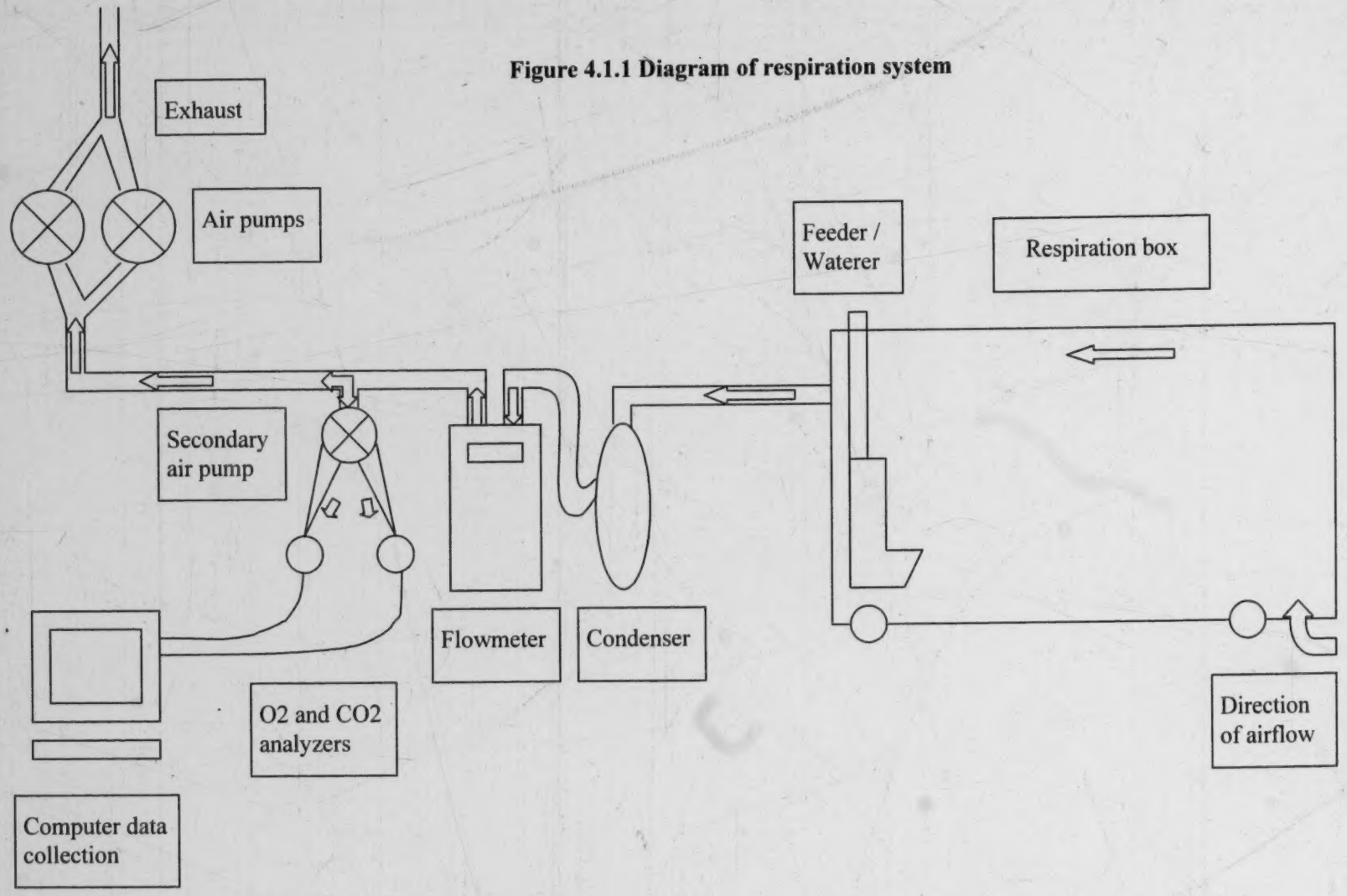
With the removal of the methane and nitrogen excretion terms, the reduced formula leads to an overestimation of heat production by approximately 1.5%.

The respiratory quotient was calculated according to the equation:

$RQ = V_{CO2} / V_{O2}$

to determine the types of substrate utilized by the sow during the measurement period.

Figure 4.1.1 Diagram of respiration system



4.1.4.2 Milk Production and Composition

Due to time constraints and the presence of piglet accessible waterers in the farrowing pen, we determined milk production by the weigh-suckle-weigh (WSW) technique. Weigh-suckle-weigh was performed with the intensive sows the day before or after respiration measurements. Measurements were taken from 0800 or 0900 to 1600 with 7 readings acquired for the day. Measurements were conducted at day 5-8 of lactation and again at day 15-20. On the morning of the procedure, piglets were removed from the sow into empty crates nearby. Approximately 20 minutes after piglet removal, sows were given 20 I.U. of oxytocin intramuscularly in the neck, and milk was manually expressed from all functional teats to obtain approximately 10 to 15 g of milk to determine milk composition. Occasionally sows did not release milk during this time and were injected with a further 20 I.U. oxytocin 20 minutes after the 7th suckling, before the piglets were returned to the sow. After milk collection, the sow and piglets were kept separated for a further 15 to 20 minutes before beginning WSW. Groups of 2 to 6 piglets were placed into a plastic container on a Sartorius EB15 scale integrated to take 20 consecutive readings (Sartorius AB, Gottingen, Germany). The average of 20 readings was taken as the group weight. Piglets were removed from the scale into a transfer box until all piglets were weighed. The litter was then placed onto the sow. Time on the sow was taken as time from last weighing to the time when all piglets had been removed from the crate. Any urination or defecation by piglets while they were with the sow or in the transfer boxes was recorded and weight was corrected using the formula of Klaver et al (1981) for urination (urine voided (g) = $2.9*W^{0.75} + 18.7$) and 10 g for each defecation (Sinclair et al, 1999). Metabolic and water losses while suckling the sow were corrected using a formula adapted from Noblet and Etienne (1986) where:

milk intake/ suckling (g) = $(Wf - Wi) + 0.210(t)*(W^{0.75})$

where Wf is final litter weight in grams, Wi is initial litter weight, t is the time on sow (minutes), and $W^{0.75}$ is the mean metabolic body weight of the piglets (litter wt/# of piglets), multiplied by the number of piglets in the litter.

In other words $W^{0.75} = ((0.001*Wi/\#\ piglets)^{0.75})*\#\ piglets$.

As noted by other researchers (Noblet and Etienne, 1986; Speer and Cox, 1984; Noblet and Etienne, 1989) the first two readings for the day appeared to be an adaptation period, and were not included in determination of milk production. Also, if litter weight after a suckling bout was similar to or lower than the initial weight, that measurement was regarded as a non-nutritive suckling (Spinka et al, 1997) and was not included in the final determination of milk yield.

4.1.4.3 Determination of Nitrogen Excretion

To measure relative urinary nitrogen excretion, spot samples of urine were obtained from intensive sows on the same day as respiration measurements. If a sample could not be acquired during calorimetry, samples were obtained the following day. Urine samples were placed in sealed plastic containers and immediately frozen (- 20°C) to prevent bacterial growth until analysis for nitrogen and creatinine content.

4.1.4.4 Determination of Diet Digestibility

To determine nutrient digestibility of the test diets, chromic oxide was added as an indigestible marker. Only the intensive sows were required to consume feed containing the indigestible marker. Therefore, chromic oxide was added after the diets were mixed by the University Feed Mill and delivered to the Swine Research Unit. Approximately 150 kg of each feed was removed from their respective bins and remixed to include 0.25% chromic oxide for determination of diet digestibility. Intensive sows received the diets containing chromic oxide for seven days prior to each gestation measurement and beginning seven days prior to the first lactation measurement, continuing until the completion of the second lactation measurement. Each sow received diet containing chromic oxide eight times during the trial. This resulted in 7 batches of chromic oxide feed mixed for each of the gestation diets and 15 and 13 batches of the

HP lactation and LP lactation diets respectively. Samples from each batch were taken for analysis of CP, DM, ether extract, NDF, ash, energy and chromic oxide content.

4.1.4.5 Determination of Body Water Content: Deuterium Oxide

Measurements for determination of D_2O dilution were completed four times to determine changes in body composition during gestation and lactation. Early and late pregnancy measurements were conducted at the University of Alberta Metabolic Unit while sows were in the respiration chamber. Early and late lactation measurements were conducted at the University of Alberta Swine Research Unit on the same day as weigh-suckle-weigh. Before respiration or WSW measurements began, sows were restrained for catheterization. One ear was cleaned using Hibitane skin cleanser (4% chlorhexidine gluconate, Zeneca Pharma, Mississauga, ON) and 70% ethanol. A BD Instyle-W I.V. 20 gauge, 30 mm long catheter with wings (Becton Dickinson, Sandy, Utah) was inserted into an ear vein with the catheter tip directed with the blood flow and held in place with 2-0 Dexon suture (Sherwood, Davis + Geck, St. Louis, MO). A 2 to 3 ml background sample was obtained as soon as the catheter had been sutured onto the ear.

A 152.4 cm, 1.6 ml extension kit with a luer lock end (Medex, Dublin, Ohio) was attached to the catheter. This was run through the top of the respiration box via a small opening during pregnancy measurements or coiled on the sows' back under duct tape for lactation measurements. The catheter and extension kit joint was secured using a 10 cm X 12 cm piece of Tegaderm transparent dressing (3M Health Care, St. Paul, Minnesota). A butterfly catheter was then placed into a second ear vein (direction against blood flow) and approximately 11 mL of physiological D_2O (0.9% saline), (99.9% APE, CDN Isotopes, Pointe Claire, Quebec) injected over a time of 1 minute. Timing of the dilution measurements began when half of the D_2O had been injected. Once all the D_2O had been injected, the catheter was flushed with 10 mL physiological heparinized saline (0.9%, Baxter Corp., Toronto, ON) and then removed from the ear vein. Blood samples were taken at approximately 15, 45, 75, 120, 180, and 240 minutes

post infusion. The extension line and catheter were flushed with saline immediately prior to and after blood sample collection. Samples were placed in 5 ml heparinized tubes (BD Vacutainer, Fisher Scientific, Mississauga, ON) and placed in a refrigerated centrifuge.

Samples were spun at 3000 RPM for 15 minutes. Plasma was decanted into a 1.5 mL eppendorf tube and frozen at -20 °C until analysis for amino acids and deuterium oxide content. Once sampling was complete, the catheter was carefully removed from the ear vein, ensuring that no suture was left in the ear and the vein had stopped bleeding before completing the rest of the day's measurements.

4.1.5 Chemical Analyses

Samples of urine, feces, plasma, and milk were stored in a - 20°C freezer prior to chemical analysis. Feed samples were stored at - 20°C until grinding and then at room temperature.

Sample grinding

Prior to analysis, feed samples were ground in a Wiley mill (Arthur Thomas Co., Philadelphia, PA) through a 1.0 mm screen. Freeze dried fecal samples were ground using a commercial coffee grinder to reduce particle size.

Nitrogen

Nitrogen (N) was determined on urine and feces by macro-Kjeldahl (AOAC, 1990). Four or five mL of urine or approximately 2 g samples of wet fecal material were weighed in duplicate and N determined according to standard procedures.

Nitrogen content of the sample was calculated using the formula:

$\%\ N = ((mL_{\text{std acid, sample}} - mL_{\text{std acid, blank}}) \times 14.0067\ mg/mmol \times N_{\text{std acid}}) \times 100\% \times 1g/1000\ mg)/\ g\ sample$

and $\%\ CP = \%\ N \times 6.25$

The nitrogen content of feed and milk were determined using a Leco FP- 428 Nitrogen Determinator, System: 601-700-900 (LECO Corporation, St. Joseph, MI). Approximately 100

mg of homogenized sample was weighed and analyzed according to standard procedure. Equipment was initially calibrated using standards of known nitrogen concentration. The protein content of the sample was automatically calculated by the system.

Urine creatinine

Urinary creatinine concentrations were determined colorimetrically using a kit (Sigma Chemical, St. Louis, MO; Catalogue No. 555-A) according to manufacturers guidelines. Urine was diluted to maintain readings within the linear range of the spectrophotometer. Dilution factors of 30X to 50X were required for sow urine samples. The concentration of creatinine in the sample was calculated as:

Creatinine (mg/dL) = Initial A_{test} – Final A_{test} / Initial A_{std} – Final A_{std}

where A is the absorbance at 500 nm.

Dry matter

Dry matter content in feed and feces was determined by weighing approximately 2 g wet samples of feed and feces and placing them in a 105°C oven for 5 hours. Samples were then removed into a dessicator, cooled to room temperature and reweighed.

To determine dry matter content of milk, samples were thawed to room temperature, weighed and placed in a freeze drier until constant weight was obtained. Samples were then removed into a dessicator, equilibrated to room temperature and reweighed. Duplicates samples were crushed and pooled for further analysis. Dry matter content of the sample was calculated by:

% DM = (wt of dried sample/ wt of original sample) * 100

Ether extract

Crude fat content in feed and freeze dried milk was determined via a Goldfisch extraction apparatus (Labconco Corp., Kansas City, MO) using petroleum ether as the solvent. Samples were weighed into filter paper cones. The filter paper was then placed into extraction tubes and covered with glass wool. Extraction tubes were then placed on the apparatus and glass beakers containing approximately 40 mL of petroleum ether were placed around the tubes. Heating

elements were turned on and ether allowed to reflux for 6 hours. Once extraction was complete, excess ether was removed and the remaining ether evaporated. Samples were then dried in a 105°C oven for at least 30 min, cooled in a dessicator and reweighed. The fat content of the sample was determined using the calculation:

% Fat = 100 X ((wt beaker + wt extract – wt blank residue) – (wt beaker)) / wt sample (g)

Neutral detergent fiber

Neutral detergent fiber content of the batch and pooled feed samples was determined according to a modified method of Goering and Van Soest (1970) using the filter bag technique. Approximately 0.5 g samples of feed were weighed in duplicate into ANKOM fiber bags. Bags were placed in NDF solution and 0.05 ml amylase per sample overnight before fiber analysis. The following morning, samples were placed in 98°C NDF solution for 70 minutes, removed, and washed 5 times in 98°C distilled water. Amylase was added (0.05 ml/ sample) in washes 2 through 4 to digest starch. Bags were air-dried, placed in acetone for 3 min, and air-dried again. Samples were then placed in 110°C oven overnight, removed into dessicator to cool to room temperature and reweighed. The fiber content of the feed samples was determined by:

% Fiber = ((wt of filter bag and fiber – wt of filter bag)/ wt of sample) * 100

Gross energy

Approximately one gram samples of feed, feces and milk samples were weighed in duplicate and analysed for gross energy using an adiabatic bomb calorimeter (Leco AC-300, LECO Corporation, St. Joseph, MI).

Ash

The ash content in feed and feces was determined by weighing samples into 50 mL pyrex beakers and placing them in a 600°C muffle furnace for at least 5 hours. Beakers were then removed into a dessicator, cooled to room temperature and reweighed. Ash in the sample was calculated using the formula:

% Ash = (wt of ashed sample/ wt of original sample)* 100

Chromic oxide determination

The chromic oxide content in batch feed samples and freeze dried feces was determined according to a method adapted from Fenton and Fenton (1979). Chromic oxide in the sample was calculated by:

% Chromic oxide = A / Sample wt (g) X B

where A is the absorbency at 440 nm, and B is the slope of the standard curve (absorbency/mg standard).

Plasma free amino acids

Plasma obtained for the deuterium oxide dilution measurements was also analysed for plasma amino acids. Single samples per sow from each measurement period were analysed for plasma amino acids according to the method of Bidlingmeyer et al (1984). Norleucine was used as the internal standard. Briefly, 200 µL of plasma, 40 µL of norleucine (2.5 µM), and 1 mL trifluoroacetic acid (0.5% TFA in methanol) were mixed in a 1.5 mL centrifuge tube, vortexed, and placed in a centrifuge at 5000 rpm for 5 minutes. The solution was then decanted into a 3 mL test tube, frozen with liquid N2, and placed on a freeze drier. After freeze-drying was complete, 50 µL of a fresh solution of 20:20:60 triethylamine:MeOH:H_2O was added to each tube, and the tube placed back onto the freeze drier. Once drying was complete, 20 µL of derivatizing solution (10% H_2O, 10% TEA, 70% MeOH, 10% phenylisothiocyanate) was added to the tube, and the contents vortexed. The tube was allowed to stand for exactly 35 minutes, then refrozen with liquid nitrogen, and placed on the freeze drier. Once dry, samples were resuspended for injection in 200 µL sample diluent (95% phosphate buffer and 5% acetonitrile), transferred to a 0.5 ml eppendorf tube using a glass pipette, and centrifuged at 5000 rpm for 5 minutes.

Feed amino acids

Feed samples obtained during the experiment were pooled within feed type (HP gestation, HP lactation, LP gestation, LP lactation). Pooled feed samples were analysed for amino acids by

Degussa AG (Hanau, Germany) using ion exchange chromatography (Llames and Fontaine, 1994). Tryptophan was analysed by fluorescence detection HPLC after alkaline hydrolysis with barium hydroxide octahydrate at 110°C for 20 hours (Fontaine et al, 1998).

Milk total amino acids

Amino acid content in dried sow's milk was determined by HPLC after hydrochloric acid hydrolysis (Sedgwick et al, 1991). Samples were pre-column derivatized with o-phthaldialdehyde (OPA). β-amino-butyric acid was used as the internal standard. Methionine, cysteine, proline and tryptophan were not determined.

Deuterium oxide

Plasma samples obtained from gestating and lactating sows were stored at the University of Alberta until analysis. At that time, samples were shipped to Toronto's Hospital for Sick Children for deuterium oxide determination. Deuterium oxide space in the body was calculated as:

D2O space (g) = (wt of solution injected * D2O conc. in solution) / equilibrium conc. in plasma

Total carbon

Batch samples of feed and fecal samples were ground in a MM2 Retsch / Brinkmann mixer mill (Brinkmann Instruments Inc., Westbury, NY) to obtain a fine powder before analysis of total carbon content. Samples were analysed using a NA1500 Carlo-Erba Elemental Analyzer (CE Elantech, Inc. Lakewood, NJ). Oven dried samples were weighed in tin boats and combusted at 1800°C. Nitrogen and carbon in the sample were separated in a gas chromatography column and automatically quantified.

Economic assessment

An economic assessment of the test diets was made by calculating margin over feed cost per sow. Average feed costs per sow per reproductive cycle were calculated from published bi-weekly feed prices for major ingredients (Bi-weekly Bulletin, Agriculture Canada website; http://www.agr.gc.ca/policy/winn/biweekly/e/arche/archbbe.htm) and quoted prices for amino

acids and supplements (Consultant Feeds) during the experimental period. Feed costs were determined using a fixed lysine cost, and with synthetic lysine price dependent on soybean meal price. Revenue from piglets was calculated from the average monthly pork prices (Index 100), based on a formula provided by AAFRD (Alberta Agriculture, Food, and Rural Development website; http://www.agric.gov.ab.ca/navigation/livestock/pigs/index.html), and the number of piglets weaned per sow.

4.1.6 Statistical Analyses

Analysis of variance for a factorial design was performed on all data using the GLM procedure of SAS Version 8.3 (SAS Institute, Cary, NC). To establish differences between group least square means, the "pdiff" option of the general linear model was used, which performs a pairwise comparison of all group least square means, based on a two-tailed T-test. Significance was determined as $p < 0.05$, and all p-values between 0.05 and 0.1 were regarded as trends.

i) Sow performance data, including sow weights and backfat depths, feed intake, litter characteristics, wean to estrus interval, percent of animals returning to service, conception rate and farrowing rate was analysed as a 2 x 2 factorial with diet and parity as the main effects. The general linear model of SAS was used to separate group means. The interaction of diet and parity was retained in the model if $p < 0.2$.

ii) Lactation measurements, comprising milk yield, milk composition and amino acid content of milk were analysed as a 2 X 2 X 2 factorial with diet, parity and stage of lactation (early or late) as the main effects. Milk yield was analysed with and without feed intake as a covariate. Group means were separated using the general linear model of SAS. All interactions were tested and retained in the model only if $p < 0.2$. If a three-factor interaction was found significant ($p < 0.05$), all relevant two-factor interactions were retained in the model.

A Pearson Correlation was performed using the CORR procedure of SAS, to attain correlations between all pertinent variables to observe whether all highly correlated factors were included in

the subsequent multiple regression. Multiple regression analyses were performed on daily milk yield, and milk composition to evaluate which sow related factors influenced milk yield and composition. The STEPWISE procedure of SAS was used to provide parameter estimates, and model correlations. Entry into the model was set as $p < 0.15$. For determination of the regression for each of the milk nutrients, other milk nutrients were not included in the analysis, as each were expected to be highly correlated, due to the methods of chemical analysis.

iii) As separate diets were utilized in gestation and lactation, nutrient digestibility coefficients were separated for gestation and lactation and analysed as 2 X 2 X 2 factorials, with diet, parity and stage (early or late) as main effects. For both factorials, the general linear model of SAS was used to separate group means. All interactions were tested and retained in the model only if $p < 0.2$. If a three-factor interaction was found significant ($p < 0.05$), all relevant two-factor interactions were retained in the model.

iv) Urinary nitrogen: creatinine ratios, and nitrogen and creatinine excretion were analysed as a 2 X 2 X 2 X 2 factorial, with diet, parity, physiological state (gestation or lactation) and stage (early or late) as main effects. The general linear model of SAS was used to separate group means. All interactions were tested and retained in the model only if $p < 0.2$. If the 4-factor interaction was found to be significant ($p < 0.05$), the full model was used for analysis. Similarly, all relevant two-factor interactions were maintained in the model if a three-factor interaction was significant ($p < 0.05$).

iv) Calorimetry results were analyzed as a 2 x 2 x 2 x 2 factorial with diet, physiological state, stage, and parity as the main effects. To determine the effects of the litter on energy expenditure, gestation and lactation results were analyzed separately as 2 x 2 x 2 factorials with diet, stage and parity as main effects. For all statistical models, the general linear model of SAS was used to separate treatment means. All interactions were tested and retained in the model if $p < 0.2$. For overall results, if the four-factor interaction was significant, the full model was used. For the overall data and the separated physiological state data, if a three-factor interaction

was significant, all relevant two-factor interactions were maintained in the model for statistical analysis.

v) Plasma amino acid concentrations were analysed as a 2 X 2 X 2 factorial with diet, physiological state, and stage as the main effects. Group means were separated using the general linear model of SAS, and interactions were included in the model if $p < 0.2$. If a three-factor interaction was found significant, all relevant two-factor interactions were maintained for analysis.

vi) Economic analysis was performed with diet as the main effect. Feed price per tonne, feed cost per sow per reproductive cycle, margin per reproductive cycle and margin over feed cost were analysed against dietary treatment. Feed price per tonne, and feed cost per sow per reproductive cycle were calculated based on fixed synthetic lysine costs, and lysine cost dependent on soybean meal price. Revenue (margin) was determined using the number of piglets weaned and the average weight of nursed piglets. Group means were separated using the general linear model of SAS, and significance determined as $p < 0.05$.

5.0 RESULTS

Of the 80 sows allocated to the experiment, five sows were removed at varying points. Data acquired from these sows, to the point of culling, was included in the final analysis. Two sows were removed due to leg problems during the experiment (one LP sow and one HP sow). Because the sow fed the HP diet was an animal allocated to intensive measurements, she was replaced by another HP (extensive) sow from her breeding group that had similar backfat and weight, commencing after her second parity farrowing. One sow from each diet treatment did not display estrus by 42 days after their second parity weaning and were subsequently culled. One LP sow did not return to estrus immediately after her second parity weaning, and was successfully rebred at her subsequent estrus (approximately three weeks after weaning). Additionally, one intensive HP sow aborted in her third parity, between early and late gestation measurements, and was replaced by another HP sow from her breeding group with similar backfat and body weight for the remainder of the intensive measurements. Missing values were accounted for, during statistical analysis, by using the general linear model of SAS.

5.1 Animal Performance

5.1.1 Performance of All Sows

Performance characteristics were measured on all sows (n = 80). No significant interactions for diet or parity were found for any of the production characteristics measured. Therefore, only main effects are described, except where indicated. This lack of interaction indicates that feeding the low protein, amino acid supplemented diets during the second parity did not significantly affect performance in the third parity.

Sow body weight changes were evaluated for the effects of diet and parity (Table 5.1.1). Sow body weight was similar across diets during gestation ($p > 0.05$). Body weight of sows fed the LP diet tended to be lower at farrowing (219.0 vs. 223.0 kg; $p = 0.07$) and was significantly

lower at weaning (210.9 vs. 218.1 kg; $p = 0.002$). As expected, parity influenced all weight measurements, as sows continued to grow throughout the experiment. Dietary treatment did not influence sow backfat at any measurement period. Parity did not influence sow backfat depth at breeding or during lactation ($p > 0.1$), but gestating sows had more backfat in their second parity than in their third parity for both early (19.7 vs. 17.7 mm) and late gestation measurements (19.4 vs. 18.5 mm; $p < 0.01$).

The characteristics used to assess reproductive adequacy of the sows were not affected by either dietary treatment or parity ($p > 0.1$). Approximately 96% of the sows displayed estrus after weaning, and were rebred. All sows displaying estrus successfully conceived, and all except one sow, that aborted, farrowed. Wean to estrus interval was numerically longer for LP sows (5.0 vs. 4.7 days), however, this was largely due to a single sow that did not display estrus until three weeks post-weaning.

Table 5.1.1 Effect of diet and parity on sow weight and backfat, and on reproductive adequacy [a]

	Diet		*Parity*		*Significance*		
	HP	**LP**	**2**	**3**	**Diet**	**Parity**	**SEM**
Sow weight (kg)							
Breeding	175.5	172.3	164.3	183.5	NS	<0.0001	1.58
Early gestation [b]	191.7	192.8	180.8	203.7	NS	<0.0001	1.38
Late gestation [c]	226.1	224.6	211.9	238.8	NS	<0.0001	1.41
Day 109	233.6	233.4	219.8	247.2	NS	<0.0001	1.41
Farrowing	223.0	219.0	207.9	234.1	0.07	<0.0001	1.53
Weaning [d]	218.1	210.9	199.4	229.6	0.002	<0.0001	1.66
Sow backfat (mm)							
Breeding	17.2	17.3	17.4	17.0	NS	NS	0.32
Early gestation	18.5	18.9	19.7	17.7	NS	<0.0001	0.32
Late gestation	18.9	19.1	19.4	18.5	NS	0.006	0.23
Farrowing	19.0	19.3	19.3	19.0	NS	NS	0.27
Weaning	17.3	17.4	17.2	17.5	NS	NS	0.32
Reproduction							
Wean-estrus (days)	4.7	5.0	5.0	4.7	NS	NS	0.23
Return to service (%)	96.2	96.2	96.3	96.1	NS	NS	2.19
Conception rate (%)	100	100	100	100	-	-	0.00
Farrowing rate (%)	98.7	100	100	98.7	NS	NS	0.90

a) values shown are least square means
b) day 39 (± 0.63 SEM) of gestation
c) day 99 (± 0.45 SEM) of gestation
d) weaning at day 21.9 (± 0.12 SEM) of lactation

Bodyweight and backfat changes throughout the experimental period were examined (Figure 5.1.1, Figure 5.1.2) to evaluate the progression of weight and backfat development throughout the production cycle. Typically, sow weight increases through gestation, as sows deposit both maternal tissue, and the fetuses develop. Weight loss during lactation is common, as the sow provides body tissue to support milk synthesis. A portion of the maternal weight gained during gestation is not lost during lactation, and the sow begins the next gestation at a higher body weight than her previous gestation. Backfat depth changes generally follow the same pattern as weight changes through the production cycle (Figure 5.1.2).

Figure 5.1.1 Sow weight throughout the complete experiment

a) values shown are least square means

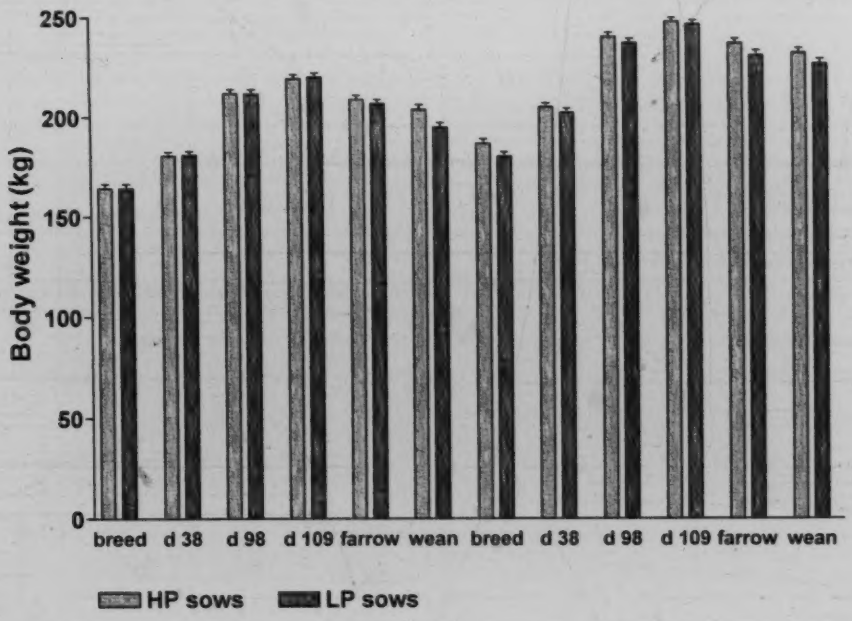
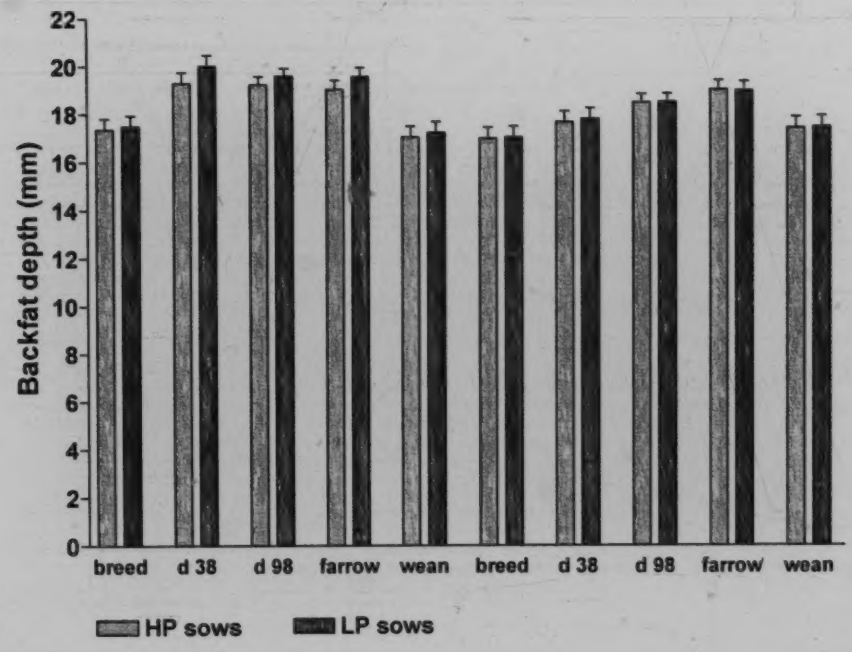


Figure 5.1.2 Sow backfat changes throughout the experimental period

a) values shown are least square means



Total live weight gain during gestation (sow plus conceptus) was significantly affected by diet (Table 5.1.2), with LP sows gaining more total mass from breeding to day 109 of gestation than HP sows (61.1 vs. 58.4 kg; $p = 0.0001$). This was mainly due to increased weight gain in the first trimester, as significantly greater gains during this period were observed (19.4 vs. 17.3 kg; $p = 0.02$), while sows on the two dietary treatments had similar gains during the remainder of gestation (32.8 vs. 33.7 kg, early-late; 8.8 vs. 7.5 kg, late-day 109; $p > 0.1$). However, total maternal (sow) gestation weight gain was not influenced by dietary treatment (47.0 vs. 48.0 kg; $p > 0.1$). Weight loss from day 109, when sows were placed on lactation feed, to the day after farrowing can be assumed to be mostly losses associated with birth. These losses were significantly greater for LP sows (-14.2 vs. -10.5 kg; $p = 0.003$), however, litter weights were similar for the two diets (Table 5.1.4). Weight loss during lactation was greater for LP sows, resulting in the lower weaning weights observed in Table 5.1.1.

Parity significantly influenced weight gain in the first trimester and from early gestation to 99 days ($p < 0.0005$), resulting in higher gestation weight gains in the third parity (63.8 vs. 55.7 kg; $p < 0.0001$). Weight changes from late gestation until sows were moved into the farrowing crate at approximately day 109 of gestation and from day 109 to post farrowing were not affected by parity ($p > 0.1$). Weight loss during lactation was significantly greater in the second parity, than in the third parity (-8.8 vs. -4.4 kg; $p = 0.003$).

Backfat changes throughout the production cycle were not influenced by dietary treatment ($p > 0.1$; Table 5.1.2). Parity did not influence the total amount of backfat gained during gestation (2.0 vs. 1.6 mm; $p > 0.1$), however, the timing of backfat deposition was significantly different for the two parities examined ($p < 0.005$). During second parity, sows deposited the majority of their backfat during the period from breeding until approximately day 39 of gestation (2.2 mm), and it appeared that sows actually lost backfat from day 39 to day 99 (-0.3 mm). During the third parity, sows gained smaller, and similar amounts of backfat during the period from breeding to early gestation (0.7 mm), and early gestation to late gestation (0.8

mm). Dietary treatment did not affect backfat loss during lactation ($p > 0.1$) Backfat loss tended to be greater ($p = 0.06$) for lactating second parity sows, than for sows in their third parity (-2.1 vs. -1.5 mm).

Table 5.1.2 Effect of diet and parity on mean changes in individual sow weight and backfat [a]

	Diet		*Parity*		*Significance*		
	HP	**LP**	**2**	**3**	**Diet**	**Parity**	**SEM**
Weight change (kg)							
Breeding to early gestation	17.3	19.4	16.5	20.2	0.02	<0.0001	0.64
Early to late gestation	33.7	32.8	31.4	35.1	NS	0.0002	0.70
Late gestation to day 109	7.5	8.8	7.9	8.4	NS	NS	0.59
Day 109 to farrowing	-10.5	-14.2	-11.7	-13.0	0.003	NS	0.85
Total Gestation [b]	58.4	61.1	55.7	63.8	0.05	<0.0001	0.99
Total Maternal [c]	48.0	47.0	43.9	51.1	NS	<0.0001	0.95
Total Lactation	-5.0	-8.3	-8.8	-4.4	0.03	0.003	0.02
Backfat change (mm)							
Breeding to early gestation	1.3	1.7	2.2	0.7	NS	<0.0001	0.24
Early to late gestation	0.4	0.2	-0.3	0.8	NS	0.003	0.25
Total Gestation	1.7	1.8	2.0	1.6	NS	NS	0.25
Total Lactation	-1.7	-1.9	-2.1	-1.5	NS	0.06	0.23

a) values shown are least square means
b) total gestation weight change is sow plus conceptus weight
c) maternal weight change measured from breeding until shortly after farrowing; represents weight gain of the sow, without conceptus products

Daily live weight changes of the sow (maternal plus conceptus) throughout gestation and lactation were calculated (Table 5.1.3). Statistical results are the same as for total weight changes, however, data were expressed in this manner to highlight the weight gain of these animals, in comparison to growth rates achieved by growing swine. Daily gain numerically increased as gestation increased. Sows fed the LP diet gained weight more quickly than HP sows from breeding to early gestation (0.50 vs. 0.45 kg/ d; $p < 0.05$). Dietary treatment did not affect weight gain from early gestation to late gestation or from late gestation (day 99 ± 0.45) to day 109 ($p > 0.1$), however overall daily weight gain was greater for LP sows (0.54 vs. 0.56 kg/ d; $p = 0.05$). Daily loss of maternal tissue during lactation was significantly greater for LP sows (-0.39 vs. -0.24 kg/ d; $p = 0.03$). Parity significantly influenced weight gains and losses. Weight changes during gestation were greater during the third parity, compared to the second parity ($p < 0.0005$), except late gestation to day 109, which was not influenced by parity ($p > 0.1$). Conversely, weight loss in lactation was greater in the second parity (-0.42 vs. -0.21 kg/day; $p = 0.003$). The average daily gain of gestating sows was 0.54 kg (540 g/ day). If we compare this to an average daily gain for finishing pigs of 750 grams, it is apparent that second and third parity sows still have a very high impetus to grow.

Table 5.1.3 Effect of diet and parity on daily live weight changes [a]

	Breeding to early gest [b]	Early gest to late gest	Late gest to day 109	Gestation	Lactation
Diet					
HP	0.45	0.56	0.71	0.54	-0.24
LP	0.50	0.55	0.84	0.56	-0.39
Significance	0.02	NS	NS	0.05	0.03
Parity					
2	0.43	0.52	0.75	0.51	-0.42
3	0.52	0.59	0.80	0.59	-0.21
Significance	<0.0001	0.0002	NS	<0.0001	0.003
SEM	0.02	0.01	0.06	0.01	0.05

a) values shown are least square means
b) weight changes given in kilograms per day

An interaction between diet and parity on weight gain from breeding to early pregnancy was observed ($p = 0.05$; Table 5.1.4). Interactions between diet and parity on weight gains during other periods were not significant ($p > 0.05$), although total weight gains during gestation tended to be influenced by the interaction ($p = 0.1$). Sows fed the HP diet demonstrated similar weight gains during both parities for the first 38 days of pregnancy. Weight gain of LP sows in early gestation was similar to HP sows during parity 2 (16.7 vs. 16.3 kg; $p > 0.05$). However, early gestation weight gain of LP sows during their third parity was greater than HP sows (22.1 vs. 18.2 kg; $p < 0.05$) and higher than weight gains during parity 2 (22.1 vs. 16.7 kg). From early gestation to late gestation, weight gains were similar for the two dietary treatments, however sows exhibited numerically greater gains in parity three. Diet and parity tended to interact on weight gains during gestation ($p = 0.1$). Total weight gain from breeding to day 109 of gestation was similar for HP and LP sows during parity 2 (55.4 vs. 55.9 kg). Total gestation weight gains were numerically greater in parity 3, however sows fed the HP diet gained less weight than LP sows (61.3 vs. 66.4 kg). The interaction between diet and parity approached significance for maternal weight gain during lactation ($p = 0.06$). Maternal weight gain during second parity gestation was slightly higher for HP sows (45.7 vs. 42.2 kg), however, sows from the two dietary treatments gained similar amounts of maternal weight during parity three (50.4 vs. 51.9 kg). Sows fed the HP diet exhibited similar lactation weight loss during the two parities. Weight loss of LP sows was numerically higher than HP sows during the second parity (-11.6 vs. -6.1 kg), but was similar to HP sows during parity 3 (-4.9 vs. -3.9 kg; $p > 0.05$).

Table 5.1.4 Interaction between diet and parity on gestation weight gain from breeding to early pregnancy [a]

	Parity 2		Parity 3			
	HP	LP	HP	LP	SEM	Interaction significance
Breeding-early gestation [b]	16.3 [g]	16.7 [g]	18.2 [g]	22.1 [h]	0.90	0.05
Early-late gestation [c]	31.9	30.9	35.5	34.8	0.99	0.8
Late gestation-day 109	7.4	8.4	7.5	9.3	0.84	0.6
Gestation [d]	55.4	55.9	61.3	66.4	1.40	0.1
Maternal gestation [e]	45.7	42.2	50.4	51.9	1.34	0.06
Lactation [f]	-6.1	-11.6	-3.9	-4.9	1.45	0.12

a) values shown are least square means
b) breeding to day 39 (± 0.63 SEM) of gestation
c) day 39 (± 0.63) to day 99 (± 0.45) of gestation
d) total weight gain (sow plus conceptus) from breeding to day 109 of gestation
e) maternal weight gain during gestation; calculated as the weight gain from breeding until shortly after farrowing
f) weight loss during a 21.9 (± 0.12) day lactation
g-h) means within rows with a common letter are not significantly different ($p > 0.05$)

5.1.2 Characteristics of Piglets Nursing All Sows

The number of piglets born and litter birth weights were not affected by dietary treatment ($p > 0.1$), however average birth weight of piglets from LP sows was lower than those from HP sows (1.33 vs. 1.39 kg; $p = 0.05$; Table 5.1.5). Sows fed the LP diet weaned fewer piglets (10.7 vs. 11.2; $p = 0.03$), resulting in significantly lower litter weaning weights (67.24 vs. 73.27 kg; $p < 0.0001$). When weaning weights were expressed on a per piglet basis, LP sows tended to wean smaller piglets than HP sows (6.35 vs. 6.61 kg; SEM = 0.10; $p = 0.07$). Sows gave birth to fewer piglets during the second parity (11.20 vs. 12.25; $p = 0.01$), however, the average birth weight of these piglets was larger (1.40 vs. 1.32 kg; $p = 0.03$). Due to these factors, birth weight of the litter was not affected by parity (15.38 vs. 15.97 kg; $p > 0.1$). Parity did not influence the number of piglets weaned, however, weaning weight of the litters was higher in the third parity (72.00 vs. 68.51 kg; $p < 0.0001$). When weaning weights were expressed on a per piglet basis, no significant difference between the parities was observed ($p > 0.1$), although piglets from sows' third parity lactation were 200 grams heavier.

Due to the common practice of the Swine Research Unit of selling one to two day old piglets for research, litter weights were recalculated after cross-fostering and sales were completed. The number of nursed piglets, and their initial and final weights were used to calculate daily growth rate of the piglets. The number of piglets nursed by the sow was not influenced by dietary treatment ($p > 0.1$), however, initial weight of litters nursing LP sows was less than those nursing HP sows (13.44 vs. 14.37 kg; $p = 0.03$). Similarly, the average initial weight of nursing piglets was lower for piglets nursing LP sows (1.37 vs. 1.43 kg; $p = 0.05$). The final (weaning) weights of nursed litters and individual piglets were significantly influenced by sow dietary treatment, with LP sows weaning lighter litters and piglets ($p < 0.005$). This was reflected in the slower growth rate of piglets nursing LP sows (242.35 vs. 261.29 g/d; $p < 0.0001$). The number of piglets nursed was not influenced by parity (10.0 vs.

9.8; $p > 0.1$), although the weight of the nursed litters was greater in the second parity (14.33 vs. 13.48 kg; $p = 0.05$). This is likely a reflection of the lower birth weight of piglets in parity three (1.32 vs. 1.40 kg; $p = 0.03$), however, calculated average initial nursed piglet weight was not different, but tended to be lower in the third parity (1.37 vs. 1.43 kg; SEM = 0.02; $p = 0.08$). Final weight of the nursed litters was not affected by parity ($p > 0.1$), however, the average weaning weight of nursed piglets was higher in parity three (7.08 vs. 6.74 kg; $p = 0.004$). This reversal is likely due to an increased milking capacity of third parity sows (Table 5.2.1), and is reflected in the higher growth rate of piglets in the third parity (256.92 vs. 246.72 g/d).

Table 5.1.5 Effect of diet and parity on litter weights at birth and weaning and nursed piglet weights and growth rate [a]

	Diet		*Parity*		*Significance*		
	HP	**LP**	**2**	**3**	**Diet**	**Parity**	**SEM**
Litter characteristics							
No. Born	11.8	11.7	11.2	12.3	NS	0.01	0.30
Litter weight [b]	16.10	15.25	15.38	15.97	NS	NS	0.37
Ave. birth weight	1.39	1.33	1.40	1.32	0.05	0.03	0.02
No. Fostered	0.2	-0.1	0.4	-0.2	NS	NS	0.25
No. Deaths	0.8	1.0	0.7	1.0	NS	NS	0.14
No. Weaned	11.2	10.7	10.8	11.1	0.03	NS	0.17
Wean weight	73.27	67.24	68.51	72.00	<0.0001	0.02	1.04
Ave. wean weight	6.61	6.35	6.38	6.58	0.07	NS	0.10
Age at weaning (d)	21.7	22.1	21.5	22.2	0.01	<0.0001	0.12
Nursed Litter Characteristics							
No. Nursed [c]	10.1	9.8	10.0	9.8	NS	NS	0.15
Initial litter weight	14.37	13.44	14.33	13.48	0.03	0.05	0.30
Ave. initial weight	1.43	1.37	1.43	1.37	NS	0.08	0.02
Final litter weight	71.18	65.46	67.28	69.36	0.0004	NS	1.11
Ave. final weight	7.09	6.72	6.74	7.08	0.002	0.004	0.08
Growth rate (g/d) [d]	261.29	242.35	246.72	256.92	<0.0001	0.02	2.98

a) values shown are least square means
b) weights given in kilograms
c) calculated as the number of piglets nursing the sow after cross-fostering and piglet sales
d) grams per day; calculated as (initial nursed litter weight subtracted from final weight divided by the number of piglets nursed) divided by the weaning age, multiplied by one thousand grams per kilogram

5.1.3 Feed Intake of All Sows

Interactions between diet and parity were not observed for feed intake measurements, therefore only main effects will be discussed. As planned, total and daily gestation feed intake was similar across dietary treatments (2.35, LP vs. 2.38 kg, HP; Table 5.1.6). Daily intake of digestible energy intake by LP sows was lower than that of HP sows (32.44 vs. 34.97 MJ; $p < 0.0001$), due to unplanned differences in energy content of the diets (Table 4.1.1). By design, gestating sows fed the LP diet consumed nearly 70 grams less protein per day, however lysine intake was similar (15.70 vs. 15.99 g; $p > 0.1$). This was expected, because synthetic lysine was added to the low protein diet to match the level in the high protein diet. Parity significantly affected gestation feed intake, with third parity sows consuming more feed, digestible energy, protein and lysine than second parity sows. This was also expected, because feed allowance in the third parity was greater, to account for the increase in sow body weight from parity 2 to parity three.

Lactation feed intake was significantly affected by diet and parity. Lactating LP sows consumed less feed overall (133.28 vs. 142.85 kg), and on a daily basis (5.80 vs. 6.31 kg; $p < 0.0001$), compared to HP sows. Energy intake of LP sows was lower than that of HP sows (84.62 vs. 95.93 MJ; $p < 0.0001$), and crude protein intake of LP sows during lactation was nearly 275 grams less than HP sows ($p < 0.0001$). Although lysine content of the two diets was similar, decreased feed intake by LP sows resulted in significantly lower daily intakes of lysine (53.32 vs. 58.70 g). Parity significantly affected feed and nutrient intake, with third parity sows consuming greater quantities of feed, digestible energy, protein and lysine than consumed in the second parity. The number of days which lactating sows consumed feed was greater in the third parity (23.21 vs. 22.35; $p < 0.0001$).

Table 5.1.6 Effect of diet and parity on feed and nutrient intake of gestating and lactating sows [a]

	Diet		*Parity*		*Significance*		
	HP	**LP**	**2**	**3**	**Diet**	**Parity**	**SEM**
Gestation [b]							
Total	257.85	254.74	243.96	268.64	NS	<0.0001	2.16
ADFI	2.38	2.35	2.25	2.48	NS	<0.0001	0.02
ADFI DE [c]	34.97	32.44	32.01	35.39	<0.0001	<0.0001	0.28
ADFI CP [d]	386.50	317.86	334.47	369.88	<0.0001	<0.0001	2.86
ADFI lys [d]	15.70	15.99	15.05	16.64	NS	<0.0001	0.13
Lactation [b]							
Total	142.85	133.28	128.14	147.99	0.0008	<0.0001	1.98
Days lac [e]	22.59	22.97	22.35	23.21	0.03	<0.0001	0.12
ADFI	6.31	5.80	5.74	6.37	<0.0001	<0.0001	0.08
ADFI DE [c]	95.93	84.62	85.58	94.97	<0.0001	<0.0001	1.22
ADFI CP [d]	1330.30	1056.07	1131.97	1254.40	<0.0001	<0.0001	16.26
ADFI lys [d]	58.70	53.32	53.09	58.93	<0.0001	<0.0001	0.76

a) values shown are least square means
b) total intake and ADFI are given in kilograms
c) daily intake of energy in MJ
d) daily intake of crude protein and lysine in grams
e) days lac = number of days sows consumed lactation feed while they were lactating (sows were placed on lactation feed upon entering the farrowing room at day 109 of gestation)

5.1.4 Performance of Sows Allocated to Intensive Measurements

Performance results for the sows allocated to intensive measurements (n = 22) were analysed separately, to ascertain whether intensive sows performed differently than all of the sows (n = 80), due to the disruption from the additional measurements these sows were subjected to. No interactions were observed for any of the performance characteristics measured, and therefore, only main effects will be discussed. Unlike the entire group, diet significantly influenced overall body weight at breeding and farrowing, with LP sows exhibiting lower body weight than HP sows ($p < 0.04$; Table 5.1.7). Additionally, body weight in late gestation tended to be lower for LP sows, compared to HP sows (221.9 vs. 227.7 kg; $p = 0.1$). Similar to the entire group, weight at weaning was significantly lower for sows fed the LP diet ($p = 0.007$). As expected, parity significantly influenced body weight for all measurement points ($p < 0.0001$). As with the entire group, diet did not affect sow backfat depths for any time point measured ($p > 0.1$). Only backfat thickness in early gestation was affected by parity, with sows exhibiting less backfat in their third parity, than in their second parity (18.0 vs. 20.5 mm, $p = 0.01$). Unlike the entire group, backfat in late gestation was not affected by parity ($p > 0.1$)

Table 5.1.7 Effect of diet and parity on weight and backfat of intensive sows, and on their wean to estrus interval [a]

	Diet		Parity		Significance		
	HP	LP	2	3	Diet	Parity	SEM
Sow weight (kg)							
Breeding	178.2	171.1	165.1	184.2	0.02	<0.0001	2.2
Early gestation [b]	194.4	190.3	181.0	203.7	NS	<0.0001	2.0
Late gestation [c]	227.7	221.9	213.0	236.6	0.1	<0.0001	2.5
Day 109	236.1	233.3	221.5	247.9	NS	<0.0001	2.5
Farrow	224.0	216.2	207.9	232.3	0.03	<0.0001	2.5
Weaning [d]	217.5	206.4	197.1	226.7	0.007	<0.0001	2.8
Sow backfat (mm)							
Breeding	17.2	17.4	17.4	17.2	NS	NS	0.5
Early gestation	19.0	19.5	20.5	18.0	NS	0.01	0.5
Late gestation	19.0	19.7	19.7	19.1	NS	NS	0.3
Farrow backfat	19.0	19.5	19.2	19.3	NS	NS	0.5
Weaning backfat	16.9	17.7	17.3	17.2	NS	NS	0.6
Wean-estrus (d)	4.8	4.8	4.8	4.9	NS	NS	0.3

a) values shown are least square means
b) day 39 (± 0.63 SEM) of gestation
c) day 99 (± 0.45 SEM) of gestation
d) weaning at day 21.9 (± 0.2 SEM) of lactation

Sows fed the LP diet gained weight faster than sows fed the HP diet from breeding to early gestation (19.2 vs. 16.2 kg; $p = 0.05$), and tended to gain faster than HP sows from late gestation until they were moved into farrowing crates at day 109 of gestation ($p = 0.07$; Table 5.1.8). Overall weight gain during gestation, however, was not influenced by dietary treatment ($p > 0.1$). Weight loss from day 109 to immediately post farrowing can be associated mainly

with birthing. Weight loss of LP sows was higher than that of HP sows (-17.1 vs. -11.9 kg; p = 0.02), although number of piglets born was similar (Table 5.1.10). Parity significantly affected weight gain from breeding to early gestation, and total weight gain during gestation, with second parity sows gaining less than the same sows in their third parity ($p < 0.05$; Table 5.1.8). Weight loss during lactation, however, was greater for second parity sows, compared to third parity sows (-11.3 vs. -5.5 kg; p = 0.03). As with the entire group, diet did not influence any of the measured backfat changes in intensive sows. Backfat deposition by sows from breeding to early gestation was higher in the second parity, compared to the third parity (3.1 vs. 0.7 mm; p = 0.004). Backfat changes from early gestation to late gestation indicated that sows lost backfat during second parity, but gained backfat during the third parity (-0.8 vs. 1.3 mm, p = 0.01). This resulted in total gestation backfat gains that were not different for the two parities ($p > 0.1$).

Table 5.1.8 Effect of diet and parity on mean changes in individual intensive sow weight and backfat [a]

	Diet		*Parity*		*Significance*		
	HP	**LP**	**2**	**3**	**Diet**	**Parity**	**SEM**
Weight change (kg)							
Breeding to early gestation	16.2	19.2	16.0	19.4	0.05	0.03	1.1
Early to late gestation	33.5	31.6	32.0	33.2	NS	NS	1.3
Late gestation to day 109	9.1	11.4	9.2	11.3	0.07	0.1	0.9
Day 109 to farrowing	-11.9	-17.1	-13.4	-15.5	0.02	NS	1.5
Total Gestation	58.5	62.2	56.9	63.9	NS	0.007	1.7
Total Lactation	-7.0	-9.7	-11.3	-5.5	NS	0.03	1.9
Backfat change (mm)							
Breeding to early gestation	1.7	2.1	3.1	0.7	NS	0.004	0.6
Early to late gestation	0.2	0.3	-0.8	1.3	NS	0.01	0.5
Total Gestation	1.9	2.4	2.3	2.0	NS	NS	0.5
Total Lactation	-2.0	-1.8	-1.7	-2.1	NS	NS	0.4

a) values shown are least square means

Daily weight gain by LP sows was higher from breeding to early gestation ($p = 0.05$), and tended to be higher from late gestation until day 109 ($p = 0.07$), than weight gain by HP sows (Table 5.1.9). As with total weight gains, daily weight gain from breeding to early gestation was higher (0.50 vs. 0.42 kg/day; $p = 0.03$), and daily weight gain from late gestation to day 109 tended to be higher ($p = 0.1$), in the third parity than in the second parity. This resulted in overall daily gestation weight gains that were higher during parity 3, compared to second parity gains (0.59 vs. 0.52 kg/day; $p = 0.007$). Conversely, weight loss during lactation was higher during the second parity, than the third parity (-0.54 vs. -0.26 kg/day; $p = 0.03$).

Table 5.1.9 Effect of diet and parity on daily live weight changes of intensive sows [a]

	Breeding to early gest [b]	Early gest to late gest	Late gest to day 109	Gestation	Lactation
Diet					
HP	0.42	0.56	0.87	0.54	-0.33
LP	0.50	0.53	1.08	0.57	-0.46
Significance	0.05	NS	0.07	NS	NS
Parity					
2	0.42	0.53	0.87	0.52	-0.54
3	0.50	0.55	1.07	0.59	-0.26
Significance	0.03	NS	0.10	0.007	0.03
SEM	0.03	0.02	0.08	0.02	0.09

a) values shown are least square means
b) weight changes are given in kilograms per day

5.1.5 Characteristics of Piglets Nursing Intensive Sows

Performance of piglets nursing intensive sows was slightly different than the overall performance of piglets. In general, a larger standard error prevented some differences from achieving significance. Dietary treatment did not influence the number of piglets born, litter weights, average piglet birth weight or number of piglets weaned ($p \geq 0.1$; Table 5.1.10). Weaning weight of the litters, however, was still lower for litters nursing LP sows (64.83 vs. 73.40 kg; $p = 0.002$). Average weight of weaned piglets was not affected by dietary treatment ($p > 0.1$). Similar to the entire group, LP sows weaned older litters than HP sows (22.2 vs. 21.7 days; $p = 0.05$). Parity did not influence any of the measured litter characteristics ($p > 0.1$), except age at weaning, where litters were weaned at an older age in the third parity, than in the second parity (22.2 vs. 21.7 days; $p = 0.05$).

Performance of litters nursed on intensive sows followed results for the entire group. The number of piglets nursed was not different for the two dietary treatments ($p > 0.1$), however, the initial weight of piglets nursing LP sows was lower than those nursing HP sows ($p = 0.05$). The average weight of the nursed piglet was not different between LP and HP sows. Final litter weight, and average final piglet weights were higher for litters nursing sows fed the HP diet ($p < 0.05$). Similarly, growth rate of piglets nursing HP was higher than for those nursing LP sows (257.5 vs. 235.0 g/d; $p = 0.004$). As with the total litter, parity did not influence any of the calculated nursed litter performance characteristics ($p > 0.1$).

Table 5.1.10 Effect of diet and parity on litter weights at birth and weaning, and weights and growth rate of piglets nursing intensive sows [a]

	Diet		*Parity*		*Significance*		
	HP	**LP**	**2**	**3**	**Diet**	**Parity**	**SEM**
Litter characteristics							
No. Born	12.0	12.1	11.6	12.6	NS	NS	0.5
Litter weight [b]	17.02	15.77	15.89	16.89	NS	NS	0.64
Ave birth weight	1.42	1.33	1.40	1.35	0.11	NS	0.04
No. Fostered	-0.1	-0.7	-0.2	-0.6	NS	NS	0.4
No. Deaths	0.5	0.8	0.7	0.6	NS	NS	0.2
No. Weaned	11.5	10.6	10.7	11.4	0.1	NS	0.3
Wean weight	73.40	64.83	67.25	70.99	0.002	NS	1.84
Ave wean weight	6.44	6.19	6.33	6.30	NS	NS	0.17
Age at weaning (d)	21.7	22.2	21.7	22.2	0.05	0.05	0.2
Nursed litter characteristics							
No. Nursed [c]	10.2	9.6	9.9	10.0	NS	NS	0.29
Initial litter weight	14.60	13.05	14.15	13.5	0.05	NS	0.54
Ave. init weight	1.44	1.36	1.44	1.36	NS	NS	0.05
Final litter weight	71.21	63.10	66.05	68.26	0.006	NS	1.99
Ave. final weight	7.01	6.59	6.71	6.89	0.03	NS	0.13
Growth rate (g/d) [d]	257.5	235.0	243.7	248.8	0.004	NS	5.24

a) values shown are least square means
b) weights are given in kilograms
c) calculated as the number of piglets nursing a sow after cross-fostering and piglet sales
d) grams per day; calculated as (initial nursed litter weight (kg) subtracted from final weight (kg) divided by the number of piglets nursed) divided by the weaning age, multiplied by one thousand grams per kilogram

5.1.6 Feed Intake of Intensive Sows

These results are similar to those obtained for the entire group of animals on the experiment. As expected, gestation feed intake of intensive sows, as total or daily intake, was not affected by dietary treatment ($p > 0.1$; Table 5.1.11). Similarly, intake of lysine was not different ($p > 0.1$). Crude protein intake by gestating LP sows was lower than HP sows ($p < 0.0001$), as planned. Digestible energy intake was also lower ($p = 0.0008$), because the digestible energy content of the LP gestation diet was lower than the digestible energy content

of the HP gestation diet (Table 4.1.1). Intake of feed and nutrients during lactation was influenced by dietary treatment, with sows fed the LP diet consuming less feed, crude protein, lysine and energy than sows fed the HP diet ($p < 0.05$). Unlike the entire group, the number of days lactating only tended to be different for the two dietary treatments (LP, 23.1 days; HP, 22.6 days; $p = 0.07$). Parity significantly influenced intake of feed and nutrients, and the number of days consuming them. Sows consumed more feed, protein, lysine and digestible energy, and consumed them for a longer period of time in parity 3, compared to parity 2 ($p < 0.05$).

Table 5.1.11 Effect of diet and parity on feed and nutrient intake of gestating and lactating intensive sows [a]

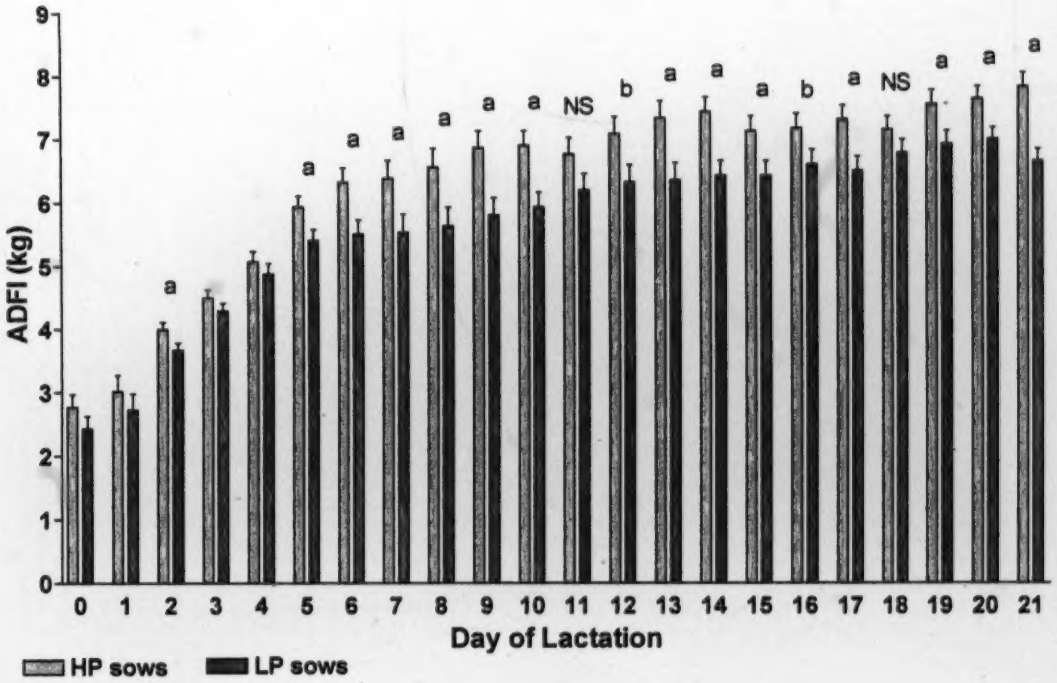
	Diet		*Parity*		*Significance*		
	HP	**LP**	**2**	**3**	**Diet**	**Parity**	**SEM**
Gestation [b]							
Total	257.58	251.92	242.22	267.28	NS	<0.0001	4.12
ADFI	2.38	2.34	2.25	2.46	NS	0.0003	0.04
ADFI DE [c]	34.91	32.24	32.08	35.07	0.0008	0.0002	0.52
ADFI CP [d]	385.94	315.88	335.14	366.68	<0.0001	0.0002	5.45
ADFI lys [d]	15.68	15.89	15.08	16.48	NS	0.0003	0.25
Lactation [b]							
Total	141.67	130.33	126.17	145.84	0.03	0.0003	3.49
Days lac [e]	22.6	23.1	22.5	23.2	0.07	0.02	0.20
ADFI	6.25	5.64	5.6	6.28	0.005	0.002	0.15
ADFI DE	94.99	82.29	83.63	93.65	0.0002	0.002	2.19
ADFI CP [d]	1317.33	1026.90	1106.86	1237.37	<0.0001	0.003	28.86
ADFI lys [d]	58.12	51.85	51.86	58.10	0.002	0.002	1.36

a) values shown are least square means
b) total intake and ADFI given in kilograms
c) daily intake of digestible energy (DE) given in MJ
d) daily intake of crude protein (CP) and lysine in grams
e) days lac = number of days sows consumed lactation feed while they were lactating (sows were placed on lactation feed upon entering the farrowing room at day 109 of gestation)

Because feed intake during lactation was recorded daily, we were able to evaluate the pattern of feed intake throughout lactation, and evaluate if dietary treatment or parity influenced this pattern. The interaction between diet and parity on feed intake was only significant on day 20 of lactation, indicating that, for most days, the pattern of feed intake was similar between HP and LP sows, and during the two parities. Dietary treatment, however, did affect how much feed sows consumed on a particular day. Sows displayed a rapid rise in feed intake during the first six days of lactation (Figure 5.1.3). After day 5 of lactation, feed intake continued to increase, at a slower rate. Feed intake was similar for the first five days (day 0 to 4), except on day 2, where HP sows consumed more feed than LP sows ($p < 0.05$). From day five, onwards, feed intake of HP sows was greater than that of LP sows ($p < 0.05$), except on day 12 and 16 where feed intake tended to be greater for HP sows ($p < 0.1$) and days 11 and 18, where sows consumed similar amounts of feed ($p > 0.1$).

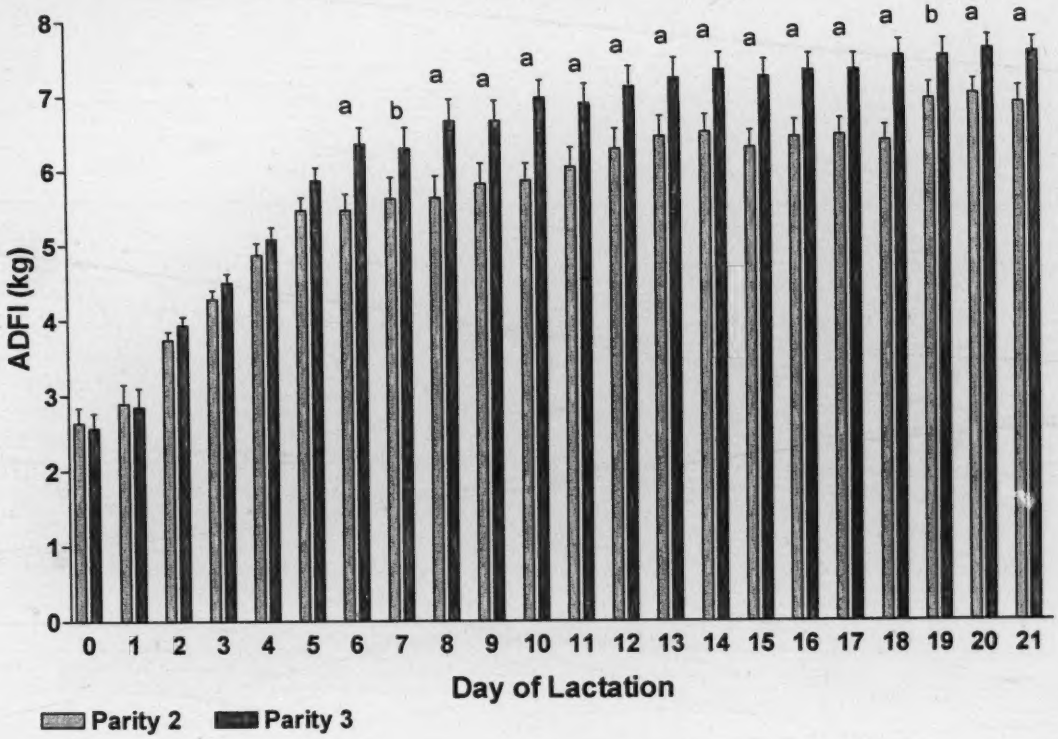
Parity did not influence feed intake during the first six days of lactation (Figure 5.1.4). However, from day 6, onward, feed intake was significantly higher (days 6, 8-18, 20, 21; $p < 0.05$), or tended to be higher (days 7, 19; $p < 0.1$) during parity 3, as compared to second parity feed intake.

Figure 5.1.3 Effect of dietary treatment on the daily feed intake pattern of intensive sows throughout lactation [a]



a) indicates day of lactation where feed intake was significantly different between the two dietary treatments ($p < 0.05$)
b) indicates day of lactation where feed intake tended to be different between the two dietary treatments ($p < 0.1$)

Figure 5.1.4 Effect of parity on the daily feed intake pattern of intensive sows throughout lactation [a]



a) indicates day of lactation where feed intake was significantly different between parity 2 and parity 3 ($p < 0.05$)
b) indicates day of lactation where feed intake tended to be different between parity 2 and parity 3 ($p < 0.1$)

5.2 Milk Yield, Composition and Amino Acids

5.2.1 Milk Yield

Milk yield, measured by weigh-suckle-weigh between days 6 and 10 (mean 7.5, SEM = 0.2 days) and 13 and 18 (mean 16.2, SEM = 0.2 days) of lactation, was calculated on a 24-hour basis, and as daily yield per nursing piglet (Table 5.2.1). Additionally, each yield measurement was analyzed with and without covariates to adjust for feed intake (yield/piglet) or feed intake and number of piglets (total yield). Sows fed the low protein diet exhibited significantly lower 24-hour milk yields (7570.56 vs. 8630.49 g; $p = 0.02$; Table 5.2.1). Because LP sows consumed less feed during lactation and nursed numerically smaller litters, milk yield was analysed with these two factors as covariates. When feed intake and number of piglets nursing were included as covariates, milk production per day was not statistically different between the two dietary treatments (LP, 8039.93 vs. HP, 8184.99 g; $p > 0.1$). Dietary treatment did not influence the amount of milk produced per nursing piglet, regardless of whether feed intake of the sow was included as a covariate or not (unadjusted: LP, 761.37 vs. HP, 814.56 g/piglet/day; $p > 0.1$). As expected, milk production was significantly higher during late lactation, regardless of how expressed ($p < 0.0003$). Parity also had a significant effect on milk yield, with third parity sows producing greater quantities of milk than sows in their second parity ($p < 0.03$).

Table 5.2.1 Effect of diet, stage of lactation and parity on milk yield [a]

	24 hr yield/piglet Unadjusted [b]	24hr yield/piglet Adjusted [c]	24 hr yield Unadjusted [d]	24 hr yield Adjusted [e]
Diet				
HP	314.56	795.00	8630.49	8184.99
LP	761.37	783.00	7570.56	8039.93
Significance	NS	NS	0.02	NS
Stage [f]				
Early	697.06	706.54	7082.84	7210.06
Late	896.86	871.46	9118.21	9014.86
Significance	<0.0001	0.0002	<0.0001	<0.0001
Parity				
2	719.03	741.84	7353.00	7615.62
3	856.90	836.46	8848.05	8609.31
Significance	0.0006	0.02	0.001	0.02
SEM	27.28	27.39	317.61	282.85

a) values shown are least square means
b) unadjusted 24 hr milk yield per piglet in grams
c) 24 hr yield of milk per piglet in grams, adjusted for feed intake as a covariate
d) unadjusted 24 hr milk yield in grams
e) 24 hr yield in grams, adjusted for feed intake and number of piglets nursing as covariates
f) early = between days 6 and 10 of lactation (mean = day 7.5, SEM = 0.2); late = between days 13 and 19 of lactation (mean = day 16.2, SEM = 0.2)

Although not statistically significant, physiologically important trends for an interaction between stage and parity on unadjusted yield per piglet ($p = 0.09$), adjusted milk yield per piglet ($p = 0.08$) and adjusted 24-hour yield ($p = 0.06$) were observed (Table 5.2.2). Unadjusted daily milk yields expressed on a total basis or per piglet basis numerically increased from early lactation to late lactation, in both parities. Milk yield in early lactation of the third parity was intermediate to early and late yields in parity 2, however, third parity sows produced greater quantities of milk during late lactation. When daily yield per piglet was adjusted for feed intake, milk yield was similar for early and late lactation during the second parity (early 692.62 g; late 791.06 g), and early lactation of parity 3 (720.46 g), but was higher during late lactation of the third parity (951.87 g). A similar pattern was observed when total daily milk yield was adjusted for feed intake and number of piglets nursing.

Table 5.2.2 Trends for interaction between stage and parity on milk yield [a]

	Parity 2		Parity 3			
	Early	Late	Early	Late	SEM	Interaction significance
Yield/piglet [b]	643.71	794.34	714.41	999.93	38.58	0.09
Yield/piglet [c]	692.62	791.06	720.46	951.87	38.86	0.08
Yield [d]	6605.06	8100.94	7585.14	10110.96	448.36	NS
Yield [e]	7074.49	8156.75	7345.64	9872.96	400.13	0.06

a) values shown are least square means
b) unadjusted daily milk yield per nursing piglet in grams
c) milk yield per piglet (grams) adjusted for sow feed intake as a covariate
d) unadjusted daily milk yield (grams)
e) daily milk yield adjusted for feed intake and number of piglets nursing as covariates

A Pearson correlation matrix was calculated, so that the correlation of all pertinent sow factors affecting milk yield and composition could be evaluated (Table 5.2.3). Additionally, auto correlation between factors could be examined. In total, twenty-five factors were included in the correlation. Due to the nature of the study, gestation feed and nutrient intakes were auto correlated, as were lactation feed and nutrient intakes. As well, crude protein and energy intakes during lactation were correlated to protein and energy intakes during gestation. Feed and nutrient intakes, and animal weights were correlated with parity. As expected, the milk fat, dry matter and energy nutrients were highly correlated with each other. This was expected, because analysis of milk nutrient concentrations was conducted in succession, on the same milk sample (i.e. milk dry matter determined, then fat determined on the dry sample, then protein determined on the dried, fat free milk sample). Interestingly, milk protein content was less highly correlated with other milk nutrients.

Table 5.2.3 Pearson correlation matrix for milk yield and composition, using a variety of sow related factors [a]

a) r-values given on upper half of table, and p-values given on lower half

Factor	Milk yield	Sow	Parity	Gest ADFI	Gest lys	Gest CP	Gest DE	Gest wt gain	Lact ADFI	Lac lys	Lac CP	Lac DE
24 hr milk yield	1	0.21	0.31	0.22	0.19	0.29	0.27	0.12	0.40	0.40	0.40	0.41
Sow	0.05	1	-0.01	-0.13	-0.13	-0.07	-0.11	-0.27	0.24	0.24	0.20	0.23
parity	0.005	0.9	1	0.51	0.51	0.34	0.47	0.39	0.42	0.41	0.32	0.39
Gestation ADFI	0.04	0.2	<0.0001	1	0.99	0.72	0.94	0.67	0.24	0.24	0.24	0.25
Gest lys (g/d)	0.09	0.2	<0.0001	<0.0001	1	0.59	0.87	0.71	0.18	0.17	0.11	0.16
Gest CP (g/day)	0.008	0.5	0.001	<0.0001	<0.0001	1	0.91	0.27	0.42	0.45	0.65	0.51
Gest DE (kcal/d)	0.01	0.3	<0.0001	<0.0001	<0.0001	<0.0001	1	0.53	0.35	0.36	0.45	0.39
Gestation wt gain	0.3	0.01	0.0001	<0.0001	<0.0001	0.01	<0.0001	1	0.009	0.0003	-0.09	-0.02
Lactation ADFI	0.0002	0.02	<0.0001	0.02	0.1	<0.0001	0.0009	0.9	1	0.99	0.92	0.99
Lac lysine (g/d)	0.0002	0.03	<0.0001	0.02	0.1	<0.0001	0.0006	0.99	<0.0001	1	0.94	0.99
Lac CP (g/d)	0.0001	0.06	0.003	0.03	0.3	<0.0001	<0.0001	0.4	<0.0001	<0.0001	1	0.96
Lac DE (MJ/d)	0.0001	0.03	0.0002	0.02	0.1	<0.0001	0.0002	0.8	<0.0001	<0.0001	<0.0001	1
Farrowing wt	0.01	0.0008	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	0.002	0.002	0.0009	0.001
Farrow backfat	0.8	0.7	0.9	0.05	0.07	0.06	0.04	0.3	0.5	0.5	0.9	0.6
Test day weight	0.08	0.0007	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.002	<0.0001	<0.0001	<0.0001	<0.0001
Lac weight loss	0.6	0.2	0.002	0.8	0.99	0.2	0.4	0.4	<0.0001	<0.0001	<0.0001	<0.0001
Backfat loss	0.2	0.5	0.4	0.7	0.7	0.6	0.6	0.3	0.8	0.8	0.96	0.8
No. of piglets	0.0005	0.0005	0.2	0.8	0.5	0.2	0.7	0.6	0.1	0.09	0.03	0.07
Day of lactation	0.0003	0.7	0.7	0.9	0.9	0.8	0.96	0.7	0.4	0.4	0.4	0.4
Ave. piglet wt	0.0001	0.7	0.5	0.5	0.5	0.4	0.4	0.6	0.6	0.6	0.5	0.6
Test day intake	<0.0001	0.09	0.002	0.09	0.2	0.002	0.01	0.9	<0.0001	<0.0001	<0.0001	<0.0001
Milk DM %	0.1	0.0004	0.4	0.7	0.99	0.1	0.4	0.4	0.5	0.4	0.1	0.3
Milk fat %	0.07	<0.0001	0.4	0.7	0.9	0.1	0.3	0.4	0.4	0.4	0.1	0.3
Milk GE kcal/kg	0.06	<0.0001	0.5	0.9	0.8	0.1	0.5	0.2	0.3	0.3	0.08	0.2
Milk CP %	0.06	0.3	0.2	0.8	0.5	0.2	0.6	0.2	0.5	0.5	0.7	0.7

Table 5.2.3 (continued) Pearson correlation matrix for milk yield and composition, using a variety of sow related factors

Factor	Farrow wt	Farrow backfat	Test day wt	Lac wt loss	Backfat loss	No. of piglets	Day of lac	Ave. piglet wt	Test day intake	Milk DM %	Milk fat %	Milk GE kcal/kg	Milk CP%
24 hr milk yield	0.28	-0.02	0.20	-0.06	-0.15	0.37	0.39	0.41	0.50	0.17	0.20	0.21	-0.21
Sow	-0.36	0.05	-0.36	-0.15	0.07	0.36	-0.05	-0.04	0.19	0.38	0.44	0.53	-0.12
parity	0.73	0.02	0.72	0.34	-0.09	0.13	-0.04	-0.07	0.33	-0.10	-0.09	-0.09	-0.15
Gestation ADFI	0.58	-0.21	0.53	0.03	-0.05	-0.03	0.01	0.08	0.19	0.04	0.05	0.01	-0.03
Gest lys (g/d)	0.54	-0.19	0.48	-0.001	-0.04	-0.07	0.02	0.07	0.13	0.0004	0.01	-0.03	-0.07
Gest CP (g/day)	0.57	-0.20	0.55	0.15	-0.06	0.13	-0.03	0.09	0.34	0.17	0.17	0.16	0.14
Gest DE (kcal/d)	0.62	-0.22	0.58	0.09	-0.06	0.04	-0.006	0.09	0.27	0.10	0.11	0.09	0.05
Gestation wt gain	0.40	-0.10	0.33	-0.10	-0.12	-0.06	0.04	0.06	-0.01	-0.10	-0.10	-0.14	-0.14
Lactation ADFI	0.34	0.08	0.45	0.60	0.03	0.17	-0.09	0.06	0.82	0.08	0.08	0.12	-0.08
Lac lysine (g/d)	0.34	0.07	0.46	0.59	0.03	0.18	-0.09	0.06	0.82	0.09	0.09	0.12	-0.07
Lac CP (g/d)	0.36	0.009	0.45	0.52	0.006	0.23	-0.08	0.08	0.75	0.16	0.17	0.20	0.04
Lac DE (MJ/d)	0.35	0.06	0.46	0.58	0.02	0.20	-0.09	0.07	0.81	0.11	0.11	0.15	-0.03
Farrowing wt	1	0.004	0.96	0.24	-0.18	0.05	-0.08	-0.03	0.22	-0.19	-0.20	-0.23	-0.08
Farrow backfat	0.97	1	0.03	0.07	-0.23	0.08	0.001	-0.05	0.10	-0.31	-0.33	-0.32	-0.10
Test day weight	<0.0001	0.8	1	0.47	-0.08	-0.04	-0.18	-0.11	0.29	-0.21	-0.23	-0.26	-0.05
Lac weight loss	0.03	0.5	<0.0001	1	0.34	-0.29	-0.08	-0.03	0.50	-0.25	-0.26	-0.26	-0.11
Backfat loss	0.1	0.04	0.5	0.002	1	-0.35	-0.03	-0.04	0.10	-0.08	-0.09	-0.08	-0.005
No. of piglets	0.7	0.5	0.7	0.008	0.0008	1	-0.13	-0.23	0.02	0.04	0.13	0.15	-0.21
Day of lactation	0.5	0.99	0.1	0.5	0.8	0.2	1	0.93	0.32	-0.10	-0.08	-0.09	-0.22
Ave. piglet wt	0.8	0.6	0.3	0.8	0.7	0.03	<0.0001	1	0.43	0.01	0.02	0.009	-0.16
Test day intake	0.05	0.4	0.008	<0.0001	0.4	0.8	0.003	<0.0001	1	-0.008	-0.10	0.007	-0.16
Milk DM %	0.09	0.004	0.06	0.02	0.5	0.7	0.4	0.9	0.9	1	0.94	0.98	0.49
Milk fat %	0.08	0.002	0.04	0.02	0.4	0.2	0.5	0.8	0.9	<0.0001	1	0.97	0.23
Milk GE kcal/kg	0.05	0.004	0.03	0.02	0.5	0.2	0.4	0.9	0.95	<0.0001	<0.0001	1	0.36
Milk CP %	0.5	0.4	0.6	0.3	0.96	0.06	0.04	0.2	0.1	<0.0001	0.03	0.0009	1

A step-wise multiple regression analysis was performed for sow milk yield, using the factors included in the Pearson correlation, to determine which factors most influenced milk yield, and to what degree (Table 5.2.4). Entry into the model was set at $p < 0.15$ to avoid the inclusion of factors that were only slightly correlated with milk yield. The most influential factor in determining milk yield was feed intake of the sow on the day of milk yield determination. Feed intake for this day was determined beginning at the late afternoon feeding of the previous day (1600 to 1600). Feed intake positively influenced milk yield such that a one-kilogram increase in feed intake resulted in a 690 gram increase in daily milk yield. Sow weight loss during lactation negatively influenced milk yield. For each kilogram of weight lost, daily milk yield decreased by 51 grams. Farrowing weight (and thus parity) positively affected milk yield, such that each additional kilogram of body weight increased milk yield by 40 grams. The number of piglets nursing the sow, and their average weight positively influenced milk yield. For each additional piglet suckling, milk yield increased by 610 grams per day, and for each kilogram increase in average nursing piglet weight, milk yield was predicted to increase by approximately 580 grams per day. The sow, herself, was a positive determinant of milk yield, indicating that individual animal variability influenced milk yield. Combining all these factors, the regression equation for sow milk yield during this experiment was:

Milk Yield (kg) = -18.74 + (0.69*lactation daily intake) – (0.051*sow wt loss) + (0.04*Sow farrowing wt) + (0.61*# of piglets) + (0.58*ave piglet wt) + (0.006*Sow)

While most of the factors remaining in the final regression were highly correlated with milk yield, sow weight loss was not well correlated (Table 5.2.3). Additionally, some factors, with a reasonable correlation to milk yield, were not included in the final regression, such as gestation and lactation crude protein intakes, and lactation lysine, feed and digestible energy intakes, suggesting that these factors were auto correlated with other factors. The inclusion of

sow weight loss, and exclusion of lactation nutrient intake in the regression suggests that the maternal supply of nutrients to the mammary gland was a more important determinant of yield, than feed intake.

Table 5.2.4 Stepwise multiple regression to determine the factors affecting milk yield (kg/day)

Variable	Parameter Estimate	Model R^2	Pr > F
Intercept	- 18.74		
Lactation test day intake (kg)	0.69	0.2334	<0.0001
Sow weight loss (kg)	- 0.051	0.3544	0.0002
Farrowing weight (kg)	0.04	0.4130	0.0111
No. of piglets nursing	0.61	0.4545	0.0398
Ave. piglet weight (kg)	0.58	0.5054	0.0242
Sow	0.006	0.5207	0.0592

5.2.2 Milk Composition

Milk nutrient composition was analysed for effects due to diet, stage and parity. Dietary treatment significantly influenced the nutrient composition of milk (Table 5.2.5). Sows fed the LP diet exhibited reduced milk dry matter, protein, milk fat, and energy concentrations, compared to milk from HP sows by ($p < 0.05$). Stage of lactation affected the protein concentration of the milk ($p = 0.003$), but not the concentration of energy, dry matter or fat ($p > 0.1$; Table 5.2.5). Across dietary treatments, the crude protein concentration of milk decreased by nearly 5% from early lactation (day 7.5) to late lactation (day 16.2). This effect was not observed for dry matter, fat and energy, although all were numerically lower during late lactation. Parity did not influence the nutrient composition of sow's milk ($p > 0.1$).

Table 5.2.5 Effect of diet, stage of lactation, and parity on the composition of sow's milk [a]

	GE (kcal/kg)	DM %	CP %	Fat %
Diet				
HP	1340.54	19.29	5.30	6.89
LP	1270.30	18.72	5.11	6.39
Significance	0.03	0.04	0.02	0.05
Stage				
Early	1324.20	19.21	5.33	6.79
Late	1286.65	18.79	5.08	6.49
Significance	NS	NS	0.003	NS
Parity				
2	1319.49	19.14	5.26	6.75
3	1291.35	18.87	5.15	6.53
Significance	NS	NS	NS	NS
SEM	22.86	0.20	0.06	0.18

a) values shown are least square means

As with milk yield, a stepwise multiple regression of sow factors on milk composition was performed. Separate regression equations were calculated for milk protein, dry matter, fat and energy. Because milk nutrients were analysed in succession, on the same milk sample, other milk composition factors were not included in each regression. Protein concentration of the milk was influenced by a variety of sow related factors (Table 5.2.6a). Milk protein concentration decreased by 0.018% for each day of lactation. The number of piglets nursing the sow also negatively influenced milk protein concentration, such that each additional suckling piglet reduced milk protein by 0.12%. Sow weight loss negatively influenced milk protein. For each kilogram of sow weight loss, milk protein concentration was reduced by 0.016%. Four factors relating to nutrient intake, which were correlated to feed intake (Table 5.2.3), had independent effects on milk protein concentration. As daily intake of crude protein and lysine increased, milk protein decreased. In addition, as daily feed intake increased, milk protein decreased. In contrast, increased digestible energy intake positively influenced the protein content of the milk. Milk yield negatively affected crude protein content of milk, such that as

daily milk yield increased, the crude protein content of milk decreased. Combining all relevant factors, the regression equation was:

Milk Protein % = 6.42 – (0.018*day of lactation) – (0.12*# of nursing piglets) – (0.016*sow wt loss) – (0.46*ADI CP) – (18.76*ADFI) + (27.61*ADI DE) – (32.60*ADI lysine) – (0.041*milk yield)

From the Pearson correlation matrix, it was apparent that very few factors were highly correlated with milk protein concentration (Table 5.2.3). Lactation feed and nutrient intake factors were poorly correlated with milk protein, however were included in the final regression. In order to determine if the negative relationship observed between nutrient intake and milk protein concentration was also true for milk protein output, a regression was additionally calculated for daily output of protein in milk (Table 5.2.6b). Daily milk protein output was positively influenced by milk yield and daily intake of dietary crude protein during lactation. For each additional kilogram of milk, daily milk protein output increased by 48.43 grams, and each additional gram of dietary protein intake increased daily milk protein by 0.12 grams. Conversely, sow weight loss, the number of piglets nursing and feed intake on the day of sampling negatively influenced milk protein output. These data suggest that the negative relationships observed between milk protein concentration and feed intake variables (Table 5.2.6a) were probably due to confounding changes in daily milk volume and concentrations of milk nutrients. Combining all relevant factors, the regression equation was:

Milk Protein g/day = 17.72 + (48.43*milk yield) + (0.12*ADI CP) – (1.42*sow wt loss) – (7.85*# of piglets nursing) – (10.08*lactation daily intake)

Table 5.2.6 Stepwise multiple regression of factors affecting milk crude protein

Variable	Parameter Estimate	Model R^2	Pr > F
a) milk CP %			
Intercept	6.42		
Day of lactation	-0.018	0.0451	0.0620
No. piglets	-0.12	0.0751	0.1228
Sow weight loss (kg)	-0.016	0.1217	0.0512
Lactation ADI CP (g)	-0.46	0.1836	0.0213
Lactation ADFI (kg)	-18.72	0.2623	0.0071
Lactation ADI DE (MJ)	27.61	0.2915	0.0913
Lactation ADI lysine (g)	-32.60	0.3315	0.0444
24 hr milk yield (kg/day)	-0.041	0.3585	0.0928
b) milk CP g/ day			
Intercept	17.72		
24 hr milk yield (kg/day)	48.43	0.9209	< 0.0001
Lactation ADI CP (g)	0.12	0.9259	0.0280
Sow weight loss (kg)	-1.42	0.9329	0.0068
No. piglets	-7.85	0.9359	0.0694
Lactation test day intake	-10.08	0.9397	0.0355

Milk dry matter percentage was most influenced by individual sow variation, indicating that milk dry matter is considerably influenced by individual animal variability (behavioral, genetic) (Table 5.2.7). Backfat depth of the sow at farrowing negatively influenced milk dry matter, such that each millimetre of backfat reduced dry matter content of the milk by 0.15%. Sow weight loss reduced milk dry matter concentration. Conversely, as daily intake of crude protein increased, milk dry matter also increased. The number of piglets nursing the sow influenced milk dry matter content, such that each additional suckling piglet reduced milk dry matter by 0.3%. Milk dry matter was also influenced by lactation intake the day of sampling, indicating that it is rapidly influenced by dietary intake changes. When all significant factors were considered, the resulting regression equation was:

Milk Dry Matter % = 16.33 + (0.0096*sow) – (0.15*farrowing backfat) – (0.058*sow wt loss) + (0.003*ADI CP) – (0.3*# of nursing piglets) = (0.31*lactation daily intake)

The majority of factors included in the milk dry matter regression were reasonably correlated with dry matter content, however, the number of piglets nursing and feed intake on the day of measurement were poorly correlated.

Table 5.2.7 Stepwise multiple regression of factors affecting milk dry matter content (%)

Variable	Parameter Estimate	Model R^2	Pr > F
Intercept	16.33		
Sow	0.0096	0.1707	0.0002
Farrow backfat depth (mm)	-0.15	0.2759	0.0015
Sow weight loss (kg)	-0.058	0.3041	0.0880
Lactation ADI CP (g)	0.003	0.3411	0.0464
No. piglets	-0.3	0.3765	0.0468
Lactation test day intake (kg)	-0.31	0.4077	0.0571

Milk fat concentration was influenced by the sow, and thus, probably reflected individual animal variation (Table 5.2.8). Additional factors influencing milk fat % were the backfat depth of the sow at farrowing, and her backfat loss during lactation; both negatively influenced milk fat content. Each millimetre increase in backfat depth at farrowing reduced milk fat by 0.23%. Additionally, for every millimetre loss in backfat during lactation, milk fat content decreased by 0.12%. Combining these factors, the regression equation was:

Milk Fat % = 3.52 + (0.011*sow) – (0.23*farrowing backfat) – (0.12*lactation backfat loss)

Table 5.2.8 Stepwise multiple regression of factors affecting milk fat (%)

Variable	Parameter Estimate	Model R^2	Pr > F
Intercept	3.52		
Sow	0.011	0.2190	<0.0001
Farrowing backfat depth (mm)	-0.23	0.3455	0.0002
Lactation backfat loss (mm)	-0.12	0.3795	0.0396

The gross energy content of milk was also influenced by animal variation (sow), farrowing backfat depth of the sow, and backfat loss during lactation (Table 5.2.9). For each millimetre of backfat at farrowing, milk energy was reduced by 26.05 kcal per kilogram of milk. Each millimetre loss in backfat depth resulted in a 13.12 kcal/kg decrease in milk energy. Combining these three factors, the resulting regression equation was:

Milk GE (kcal/kg) = 798.31 + (1.51*sow) – (26.05*farrowing backfat) – (13.12*lactation backfat loss)

For both milk fat and energy content, sow and farrowing backfat depth were reasonably correlated with the examined factor, however, lactation backfat loss was poorly correlated.

Table 5.2.9 Stepwise multiple regression of factors affecting milk gross energy content (kcal/kg)

Variable	Parameter Estimate	Model R^2	Pr > F
Intercept	798.31		
Sow	1.51	0.2813	<0.0001
Farrowing backfat depth (mm)	- 26.05	0.3992	0.0002
Lactation backfat loss (mm)	- 13.12	0.4268	0.0595

5.2.3 Milk Amino Acids

Analysed amino acids accounted for approximately 71 g per 16 g of nitrogen, and was not different for the two dietary treatments (SUM 70.77 vs. 71.26 g AA/ 16 g N; $p > 0.1$; Table 5.2.10). Methionine, cystine, and tryptophan are damaged or destroyed during acid hydrolysis, and therefore were not included. Due to the method employed, proline was also not measured. The main effects of stage and parity did not influence the amino acid content of milk ($p > 0.1$), nor were there any interactions; therefore, only diet effects are presented. All analysed amino acids, except glycine, were not influenced by dietary treatment ($p > 0.3$). The milk protein from sows fed the LP diet contained a higher concentration of glycine (2.79 vs. 2.55 g/ 16 g N; $p = 0.05$).

Table 5.2.10 Total amino acid content of milk protein (g AA/ 16 g N) [a]

Amino acid	High Protein	Low Protein	SEM [b]	Significance
Indispensable				
Arginine	4.38	4.51	0.11	0.4
Histidine	2.82	2.83	0.07	0.9
Isoleucine	3.29	3.28	0.07	0.9
Leucine	6.48	6.52	0.14	0.8
Lysine	7.29	7.40	0.18	0.7
Phenylalanine	3.07	3.08	0.07	0.9
Threonine	3.06	3.03	0.09	0.8
Valine	4.26	4.25	0.09	0.9
Dispensable				
Alanine	2.79	2.75	0.06	0.6
Aspartate	6.33	6.20	0.12	0.5
Glutamate	16.53	16.71	0.35	0.7
Glycine	2.55	2.79	0.07	0.05
Serine	3.51	3.57	0.06	0.6
Taurine	0.44	0.43	0.02	0.7
Tyrosine	2.74	2.72	0.06	0.8
SUM	70.77	71.26	1.52	0.8

a) values shown are least square means
b) SEM = standard error of the mean

5.3 Diet Composition and Amino Acid Balance

The data on amino acid composition of the diets and intake of the sows is presented below on a total amino acid basis. The reasons for presenting the data in this manner are that the feed analysis only provided total amino acids, and insufficient research has been conducted on amino acid digestibility and availability in feedstuffs for sows to calculate digestibility with any confidence.

5.3.1 Gestation Diets and Intake

Diets were formulated to contain similar concentrations of lysine and threonine by the addition of crystalline lysine and threonine to the low protein (LP) diet. Due to some variations in the amino acid content of the feed ingredients, from their expected amino acid composition (NRC, 1998), the lysine content of the LP gestation diet was slightly higher than in the HP diet, while the threonine content was lower than in the HP diet (Table 5.3.1, Table 5.3.2). For purposes of comparison to NRC (1998) recommended dietary concentrations, the amino acid requirements were calculated using the NRC equations, and the actual observed performance and measured feed intake of the sows, for each parity. Both diets provided adequate concentrations of amino acids for sows to meet their predicted total amino acid requirements in both parities.

Actual daily amino acid intake was also compared to the NRC (1998) recommendations. Feed intake for each sow during gestation was determined using a feeding schedule adopted by the University of Alberta Swine Research and Technology Centre. This feeding schedule is based on weight and backfat at breeding, and gives expected weight and backfat gains (Aherne and Foxcroft, 2000). According to this schedule, sows were offered slightly greater quantities of feed than suggested by the NRC (1998). Daily intake of sows during parity 2 was 2.24 kg for LP sows and 2.26 kg for HP sows (SEM = 0.03), and was 2.46 kg for LP sows and 2.50 kg for HP sows (SEM = 0.03) during their third parity.

When daily intake of total amino acids was compared between dietary treatments, it was apparent that the sows fed the LP gestation diet achieved the experimental objective of consuming less protein and amino acids. However, the LP diet still provided an excess daily intake of all indispensable amino acids, according to NRC (1998).

Table 5.3.1 Total amino acid content of the gestation diets and daily intake of amino acids during the second parity

		HP diet	LP diet		HP diet		LP diet		
Amino Acid	**NRC (g/kg) [a]**	**AA (g/kg) [b]**	**AA (g/kg) [b]**	**NRC daily [a]**	**Daily intake [c]**	**% NRC [d]**	**Daily intake [c]**	**% NRC**	**Intake SEM**
Arginine	0.4	8.7	6.2	0.8	19.6	2450	13.9	1738	0.19
Cystine	2.1	3.4	2.9	4.8	7.7	160	6.5	135	0.08
Histidine	1.7	3.8	2.8	3.9	8.6	221	6.3	162	0.08
Isoleucine	3	5.6	4.3	6.8	12.6	185	9.6	141	0.13
Leucine	4.6	11.2	8.6	10.3	25.3	246	19.2	186	0.25
Lysine	5.4	**6.6**	**6.8**	12.2	14.9	122	15.2	125	0.17
Methionine	1.4	2.7	2.1	3.1	6.1	197	4.7	152	0.06
Met + Cys	3.5	6.1	5	7.9	13.8	175	11.2	142	0.07
Phenylalanine	3	8	6.6	6.7	18	269	14.8	221	0.19
Threonine	4.2	**5.6**	**5.2**	9.4	12.6	134	11.6	123	0.14
Tryptophan	1	2	1.5	2.3	4.5	196	3.4	148	0.04
Valine	3.6	7.3	5.9	8.1	16.5	204	13.2	163	0.17

a) NRC (1998) predicted total amino acid requirements for a 164 kg sow, gaining 57 kg, consuming 2.25 kg and 7.65 Mcal DE per day, carrying 12 piglets
b) analysed amino acid content (Degussa AG)
c) actual daily intake of total amino acids in grams
d) actual daily intake as a percentage of estimated NRC requirement

Table 5.3.2 Total amino acid content of the gestation diets and daily intake of amino acids during the third parity

		HP diet	LP diet		HP diet		LP diet		
Amino Acid	NRC (g/kg) [a]	AA (g/kg) [b]	AA (g/kg) [b]	NRC daily [a]	Daily intake [c]	% NRC [d]	Daily intake [c]	% NRC	Intake SEM
Arginine	0.3	8.7	6.2	0.9	21.8	2422	15.3	1700	0.21
Cystine	2.0	3.4	2.9	5.2	8.5	163	7.2	138	0.09
Histidine	1.7	3.8	2.8	4.2	9.5	226	6.9	164	0.09
Isoleucine	3.0	5.6	4.3	7.4	14.0	189	10.6	143	0.14
Leucine	4.4	11.2	8.6	11.0	28.0	255	21.2	193	0.28
Lysine	5.3	**6.6**	**6.8**	13.1	16.5	126	16.8	128	0.2
Methionine	1.4	2.7	2.1	3.4	6.8	200	5.2	153	0.07
Met + Cys	3.4	6.1	5.0	8.5	15.3	180	12.3	145	0.08
Phenylalanine	2.9	8.0	6.6	7.1	20.0	282	16.3	230	0.21
Threonine	4.1	**5.6**	**5.2**	10.1	14.0	139	12.8	127	0.16
Tryptophan	1.0	2.0	1.5	2.5	5.0	200	3.7	148	0.05
Valine	3.5	7.3	5.9	8.7	18.3	210	14.5	167	0.19

a) NRC (1998) predicted total amino acid requirements for a 184 kg sow, gaining 63 kg, consuming 2.48 kg and 8.45 Mcal DE per day, carrying 13 piglets
b) analysed amino acid content (Degussa AG)
c) actual daily intake of total amino acids in grams
d) actual daily intake as a percentage of NRC requirement

With the reduction in dietary crude protein and addition of synthetic lysine and threonine, the amino acid profile of the LP diet more closely matched the ideal ratio of total amino acids proposed by the NRC modeling program (1998) than the HP diet profile (Table 5.3.3). The NRC total amino acid requirements were calculated using a sow matching the average of the sows, across both parities, from this experiment. Threonine in the low protein diet was slightly below its optimal ratio to lysine, because the lysine content of the low protein diet was higher, and threonine content lower, than expected. Daily intake, however, was more than adequate according to NRC (1998) (Table 5.3.1; Table 5.3.2). Due to the amino acid content of intact protein sources, however, several amino acids were present in the diet well above their ideal ratio, namely arginine, leucine, and phenylalanine.

Table 5.3.3 Ratio of total amino acids to lysine in the gestation diets as compared to NRC (1998)

Amino Acid	High Protein	Low Protein	NRC [a]
Arginine	131.8	91.2	5.7
Cystine	51.5	42.6	37.7
Histidine	57.6	41.2	32.1
Isoleucine	84.8	63.2	56.6
Leucine	169.7	126.5	84.9
Lysine	**100.0**	**100.0**	**100.0**
Methionine	40.9	30.9	26.4
Met + Cys	92.4	73.5	64.2
Phenylalanine	121.2	97.0	54.9
Threonine	**84.8**	**76.5**	**77.4**
Tryptophan	30.3	22.1	18.9
Valine	110.6	86.8	66.0

a) ideal ratio of total amino acids for a 174 kg sow gaining 59 kg and carrying 12 piglets, consuming 2.36 kg and 8.05 Mcal DE per day

5.3.2 Lactation Diets and Intake

Diets were formulated to contain 19.31% CP in the HP diet, and 16.31% CP in the LP diet. However, actual average crude protein contents of the diets were 21.08% CP, and 18.22% CP for the HP and LP lactation diets, respectively (Table 4.3), due to ingredient variation. Lysine concentrations of the lactation diets were similar, as planned (Table 5.3.4, Table 5.3.5). However threonine concentration of the LP diet was slightly lower than in the HP diet. Diets were formulated to meet the amino acid requirements of a 175 kg sow, losing no weight, and nursing piglets gaining 200 grams per day. As sows began gestation at higher weights, and gained more than expected (Table 5.1.1; Table 5.1.2), these sows entered lactation at an average of 208 kg in parity 2 and 234 kg in parity 3. Total amino acid requirements for each parity were determined with the NRC modelling program (1998), using actual mean weights and performance for the sows on the experiment. The amino acid concentrations (g/kg) of the HP lactation diet were sufficient to meet the determined NRC (1998) requirement, except for lysine. The concentrations of lysine, valine and isoleucine in the LP lactation diet were below requirement, and threonine concentration was marginal. Feed intake estimated by the NRC program was similar to the average of the two dietary treatments, for each parity (Table 5.3.4; Table 5.3.5). Mean lactation feed intake during the second parity was 5.42 kg/day for LP sows and 6.05 kg/day for HP sows (SEM = 0.12). During the third parity, average daily lactation feed intake was 6.17 kg for LP sows and 6.57 kg for HP sows (SEM = 0.11). Although HP sows consumed more feed than predicted by the NRC (1998) model, these sows were still deficient in lysine during both their second and third lactation, according to the calculated NRC (1998) requirements. Because sows fed the LP diet consumed less feed during lactation than predicted by the NRC (1998) model, they consumed inadequate lysine, valine, isoleucine, threonine and methionine to meet their total amino acid requirements for these amino acids, according to NRC (1998), during their second parity. During their third parity, LP sows did not

consume sufficient feed to meet their predicted lysine, valine and isoleucine requirements, and consumed marginal threonine (Table 5.3.5).

Table 5.3.4 Total amino acid content of the lactation diets and daily intake of amino acids during the second parity

		HP diet	LP diet		HP diet		LP diet		
Amino Acid	NRC (g/kg) [a]	AA (g/kg) [b]	AA (g/kg) [b]	NRC daily [a]	Daily intake [c]	% NRC [d]	Daily intake [c]	% NRC	Intake SEM
Arginine	5.3	12.4	8.6	30.7	75.1	245	46.6	152	1.31
Cystine	2.3	3.9	3.6	13.4	23.6	176	19.5	146	0.45
Histidine	4.0	5.1	4.9	23.0	30.9	134	26.6	116	0.60
Isoleucine	5.7	8.0	5.6	32.5	48.4	149	**30.4**	94	0.85
Leucine	11.1	15.0	13.1	63.7	90.8	143	71.0	111	1.70
Lysine	10.2	**9.3**	**9.2**	58.6	**56.3**	96	**49.9**	85	1.11
Methionine	2.6	3.1	2.7	14.7	18.8	128	**14.6**	99	0.35
Met + Cys	4.9	7.0	6.3	28.2	42.4	150	34.2	121	0.40
Phenylalanine	5.5	10.7	9.1	31.3	64.8	207	49.4	158	1.20
Threonine	6.5	**7.0**	**6.5**	37.3	42.4	114	**35.3**	95	0.81
Tryptophan	1.8	2.5	2.2	10.6	15.1	142	11.9	112	0.28
Valine	8.7	9.3	8.0	49.9	56.3	113	**43.4**	87	1.05

a) NRC (1998) predicted total amino acid requirements for a 208 kg sow, losing 7.8 kg, consuming 5.73 kg and 20.4 Mcal DE per day, nursing 10 piglets gaining 247 g/day for 22 days
b) analysed amino acid content (Degussa AG)
c) actual daily intake of total amino acids in grams
d) actual daily intake as a percentage of NRC requirement

Table 5.3.5 Total amino acid content of the lactation diets and daily intake of amino acids during the third parity

Amino Acid	NRC (g/kg) [a]	HP diet AA (g/kg) [b]	LP diet AA (g/kg) [b]	NRC daily [a]	HP diet Daily intake [c]	HP diet % NRC [d]	LP diet Daily intake [c]	LP diet % NRC	Intake SEM
Arginine	5.2	12.4	8.6	33.4	81.4	244	53.1	159	1.22
Cystine	2.3	3.9	3.6	14.4	25.6	178	22.2	154	0.42
Histidine	3.9	5.1	4.9	24.8	33.5	135	30.2	122	0.56
Isoleucine	5.5	8.0	5.6	34.9	52.5	150	**34.6**	99	0.79
Leucine	10.7	15.0	13.1	68.2	98.5	144	80.8	118	1.58
Lysine	9.9	**9.3**	**9.2**	63.0	**61.1**	97	**56.8**	90	1.03
Methionine	2.5	3.1	2.7	15.9	20.4	128	16.7	105	0.33
Met + Cys	4.8	7.0	6.3	30.3	46.0	152	38.9	128	0.38
Phenylalanine	5.3	10.7	9.1	33.7	70.3	209	56.2	167	1.11
Threonine	6.3	**7.0**	**6.5**	40.2	46.0	114	**40.1**	100	0.75
Tryptophan	1.8	2.5	2.2	11.3	16.4	145	13.6	120	0.26
Valine	8.4	9.3	8.0	53.3	61.1	115	**49.4**	93	0.97

a) NRC (1998) predicted total amino acid requirements for a 234 kg sow, losing 3.8 kg, consuming 6.38 kg and 22.7 Mcal DE per day, nursing 10 piglets gaining 257 g/day for 23 days
b) analysed amino acid content (Degussa AG)
c) actual daily intake of total amino acids in grams
d) actual daily intake as a percentage of NRC requirement

Compared to the HP diet, the balance of indispensable amino acids provided by the LP lactation diet more closely matched the ideal amino acid profile suggested by NRC (1998), using the average performance of lactating sows in this experiment (Table 5.3.6). Despite the decrease in crude protein, several amino acids were still above their ideal ratio to lysine, demonstrating that excesses still existed in the low protein diet.

Table 5.3.6 Ratio of total amino acids to lysine in the lactation diets as compared to NRC (1998)

Amino Acid	High Protein	Low Protein	NRC [a]
Arginine	133.3	93.5	53
Cystine	41.9	39.1	23
Histidine	54.8	53.3	39
Isoleucine	86.0	60.9	55
Leucine	161.3	142.4	108
Lysine	**100.0**	**100.0**	100
Methionine	33.3	29.3	25
Met + Cys	75.2	68.5	48
Phenylalanine	115.1	98.9	53
Threonine	**75.2**	**70.7**	64
Tryptophan	26.9	23.9	18
Valine	100.0	87.0	85

a) ideal ratio of total amino acids for a 211 kg sow losing 5.2 kg bodyweight, consuming 6.07 kg and 21.60 Mcal DE per day, nursing 10 piglets gaining 250 g/day for 23 days

5.3.3 Amino Acid Intake of Intensive Sows

Because of the extra measurements imposed on the intensive sows, their amino acid intake during lactation was calculated separately, and compared to the intake pattern of all of the sows. The intensive sows receiving both dietary treatments consumed similar quantities ($p > 0.1$) of lactation feed compared to the average of the entire group (HP: 6.00 vs. 6.05 kg, parity 2, SEM = 0.18; 6.51 vs. 6.57 kg, parity 3, SEM = 0.17; LP: 5.22 vs. 5.42 kg, parity 2, SEM = 0.16; 6.05 vs. 6.17 kg, parity 3, SEM = 0.14). The amino acid requirements of the intensive sows were calculated according to the NRC model (1998), using their average performance, during each parity. Similar to the results with the extensive sows, intensive sows fed the HP diet did not consume sufficient lysine, and intensive LP sows did not consume adequate lysine, methionine, threonine, valine and isoleucine during the second parity to meet the requirements for these amino acids, according to NRC (Table 5.3.7). Based on the NRC model, during their third parity lactation, HP intensive sows were slightly lysine deficient, similar to the entire HP group (Table 5.3.8). Due to slightly lower growth rate of piglets nursing intensive sows, compared to the average of piglets nursing all of the sows, intensive LP sows were predicted to be deficient in lysine and valine, and marginal for isoleucine during their third parity.

Table 5.3.7 Amino acid content of the lactation diets and daily intake of amino acids during the second parity: Intensive sows

		HP diet	LP diet		HP diet		LP diet		
Amino Acid	NRC (g/kg) [a]	AA (g/kg) [b]	AA (g/kg) [b]	NRC daily [a]	Daily intake [c]	% NRC [d]	Daily intake [c]	% NRC	SEM
Arginine	5.3	12.4	8.6	29.8	74.3	249	44.9	151	2.13
Cystine	2.3	3.9	3.6	13.2	23.4	177	18.8	142	0.76
Histidine	4.0	5.1	4.9	22.5	30.5	136	25.6	114	1.01
Isoleucine	5.7	8.0	5.6	31.9	47.9	150	**29.2**	92	1.38
Leucine	11.1	15.0	13.1	62.5	89.8	144	68.4	110	2.84
Lysine	10.2	**9.3**	**9.2**	57.4	**55.7**	97	**48.0**	84	1.88
Methionine	2.6	3.1	2.7	14.4	18.6	129	**14.1**	98	0.59
Met + Cys	2.9	7.0	6.3	27.6	41.9	152	32.9	119	0.66
Phenylalanine	5.5	10.7	9.1	30.7	64.1	209	47.5	155	2.00
Threonine	6.5	**7.0**	**6.5**	36.6	41.9	114	**33.9**	93	1.37
Tryptophan	1.9	2.5	2.2	10.4	15.0	144	11.5	110	0.48
Valine	8.7	9.3	8.0	48.9	55.7	114	**41.8**	85	1.79

a) NRC (1998) predicted total amino acid requirements for a 208 kg sow, losing 9.2 kg, consuming 5.60 kg and 19.94 Mcal DE per day, nursing 10 piglets gaining 244 g/day for 23 days
b) analysed amino acid content (Degussa AG)
c) actual daily intake of total amino acids in grams
d) actual daily intake as a percentage of NRC requirement

Table 5.3.8 Amino acid content of the lactation diets and daily intake of amino acids during the third parity: Intensive sows

		HP diet	LP diet		HP diet		LP diet		
Amino Acid	NRC (g/kg) [a]	AA (g/kg) [b]	AA (g/kg)	NRC daily [a]	Daily intake [c]	% NRC [d]	Daily intake	% NRC	SEM
Arginine	5.2	12.4	8.6	32.4	80.7	249	52.0	161	2.32
Cystine	2.2	3.9	3.6	14.1	25.4	180	21.8	155	0.81
Histidine	3.8	5.1	4.9	24.1	33.2	138	29.7	123	1.08
Isoleucine	5.4	8.0	5.6	33.9	52.1	154	**33.9**	100	1.50
Leucine	10.5	15.0	13.1	66.2	97.6	148	79.3	120	3.04
Lysine	9.7	**9.3**	**9.2**	61.2	**60.5**	99	**55.7**	91	1.99
Methionine	2.5	3.1	2.7	15.4	20.2	131	16.3	106	0.63
Met + Cys	4.7	7.0	6.3	29.5	45.6	155	38.1	129	0.72
Phenylalanine	5.2	10.7	9.1	32.8	69.7	213	55.1	168	2.15
Threonine	6.2	**7.0**	**6.5**	39.1	45.6	116	39.3	101	1.46
Tryptophan	1.7	2.5	2.2	11.0	16.3	149	13.3	122	0.51
Valine	8.2	9.3	8.0	51.8	60.5	117	**48.4**	94	1.88

a) NRC (1998) predicted total amino acid requirements for a 232 kg sow, losing 2.6 kg, consuming 6.28 kg and 22.36 Mcal DE per day, nursing 10 piglets gaining 249 g/day for 23 days
b) analysed amino acid content (Degussa AG)
c) actual daily intake of total amino acids in grams
d) actual daily intake as a percentage of NRC requirement

5.4 Apparent Fecal Digestibility of Nutrients

Nutrient digestibility was measured in the intensive sows only (n = 22). Apparent digestibility coefficients were determined in gestation and lactation, and results were separated by physiological state, because different diets were used for the two physiological states, and feeding regimen was dissimilar. The apparent digestibility of crude protein (N x 6.25) and energy in the LP gestation diet was lower than for the HP gestation diet ($p < 0.01$; Table 5.4.1), while the digestibilities of dry matter and carbon were similar ($p > 0.1$). Stage of gestation, and parity did not influence the digestibility of any of the nutrients analysed ($p > 0.1$).

Table 5.4.1 Effect of diet, stage and parity on the apparent digestibility coefficients of nutrients during gestation [a]

	Dry Matter	Crude protein	Energy	Carbon
Diet				
HP	79.8	82.5	81.7	81.3
LP	79.4	79.8	80.7	80.9
Significance	NS	0.0001	0.006	NS
Stage				
Early	79.5	81.0	81.4	81.2
Late	79.7	81.3	81.0	81.0
Significance	NS	NS	NS	NS
Parity				
2	79.6	80.6	81.2	81.1
3	79.6	81.7	81.2	81.1
Significance	NS	NS	NS	NS
SEM	0.3	0.5	0.3	0.3

a) values shown are least square means

Significant interactions between diet and parity on the apparent digestibility coefficients of dry matter, carbon and energy during gestation were observed (Table 5.4.2; $p < 0.01$). A trend towards an interaction between diet and parity on apparent crude protein digestibility was similarly observed ($p = 0.1$). Dry matter and carbon digestibilities followed similar patterns. The digestibilities of dry matter and carbon in the HP diet decreased with increasing parity, whereas, the dry matter and carbon digestibilities were similar across parities for the LP diet. Dry matter and carbon digestibilities were higher for the HP diet, compared to the LP diet during the second parity (DM, 80.4 vs. 78.8%; C, 82.0 vs. 80.3%; $p < 0.05$), however, the digestibilities of dry matter and carbon were similar for the two diets in parity three (DM, 79.2 vs. 80.0%; C, 80.7 vs. 81.5%; $p > 0.05$). Energy digestibility coefficients for the HP and LP diets were not affected by parity, and were similar across diets during the third parity (81.2 vs. 81.2%; $p > 0.05$). The digestibility of energy in parity 2, however, was higher for the HP diet, compared to the LP diet (82.3 vs. 80.1%; $p < 0.05$). The digestibility of crude protein was similar across parities for the HP diet, whereas the crude protein digestibility of the LP diet numerically increased from the second to third parity (78.7 vs. 80.9%).

Table 5.4.2 Interaction between diet and parity on apparent digestibility coefficients of nutrients in the gestation diets [a]

	High Protein		Low Protein			Interaction
	Parity 2	Parity 3	Parity 2	Parity 3	SEM	significance
DM	80.4 [c]	79.2 [b]	78.8 [b]	80.0 [bc]	0.4	0.006
CP	82.5	82.5	78.7	80.9	0.7	0.1
Energy	82.3 [b]	81.2 [bc]	80.1 [c]	81.2 [c]	0.4	0.006
Carbon	82.0 [c]	80.7 [b]	80.3 [b]	81.5 [bc]	0.4	0.006

a) values shown are least square means
b-c) means within rows with a common letter are not significantly different ($p > 0.05$)

Dietary treatment significantly influenced the digestibility of analysed nutrients during lactation (Table 5.4.3). The apparent digestibility coefficients for dry matter, crude protein, energy and carbon were lower for the LP lactation diet, compared to the HP diet ($p < 0.05$). Stage of lactation did not influence the digestibility of dry matter or carbon ($p > 0.1$), but crude protein and energy digestibilities were reduced as lactation progressed ($p < 0.01$). Increasing parity reduced the digestibility of energy (82.3 vs. 81.1%; $p < 0.05$) and tended to reduce carbon digestibility ($p < 0.1$), but did not affect dry matter or crude protein digestibility coefficients ($p > 0.1$).

Table 5.4.3 Effect of diet, stage and parity on apparent digestibility coefficients of nutrients during lactation [a]

	Dry Matter	Crude protein	Energy	Carbon
Diet				
HP	80.1	82.9	83.0	82.0
LP	79.0	77.9	80.4	80.4
Significance	0.04	<0.0001	<0.0001	0.006
Stage				
Early	79.8	81.5	82.4	81.6
Late	79.3	79.2	81.1	80.8
Significance	NS	0.0004	0.009	NS
Parity				
2	79.9	80.4	82.3	81.7
3	79.3	80.4	81.1	80.7
Significance	NS	NS	0.02	0.08
SEM	0.4	0.5	0.4	0.4

a) values shown are least square means

5.5 Nitrogen Excretion and Plasma Amino Acids

5.5.1 Urinary Nitrogen Excretion

The main effects of diet, physiological state, stage and parity were examined for the excretion of nitrogen and creatinine in spot samples of urine, and the ratio of nitrogen: creatinine. Nitrogen concentration of urine was not affected by diet or stage, but was significantly influenced by physiological state and parity (Table 5.5.1). Nitrogen in the urine samples was lower during gestation than lactation (9.25 vs. 11.76 mg/mL; $p = 0.02$) and during the second vs. third parity (9.35 vs. 11.65 mg/mL; $p = 0.03$). Creatinine content of the urine samples was not significantly affected by any of the main effects tested. Relative nitrogen excretion, as measured by the ratio of nitrogen to creatinine, was significantly lower in sows fed the LP vs. HP diets (6.22 vs. 8.37; $p = 0.0001$), a reduction of nearly 26%. The nitrogen: creatinine ratio was affected by physiological state and parity, but not by stage. Relative nitrogen excretion was lower during gestation than lactation (6.50 vs. 8.10; $p = 0.003$), and lower during the second parity (5.75 vs. 8.84; $p < 0.0001$).

Table 5.5.1 Effect of diet, physiological state, stage of gestation or lactation and parity on excretion of creatinine, nitrogen and their ratio in urine spot samples [a]

	Nitrogen (mg/mL)	Creatinine (mg/mL)	N:Cr
Diet			
HP	10.62	1.57	8.37
LP	10.38	1.74	6.22
Significance	NS	NS	0.0001
Physiological state			
Gestation	9.25	1.66	6.50
Lactation	11.76	1.64	8.10
Significance	0.02	NS	0.003
Stage			
Early	10.53	1.66	7.21
Late	10.48	1.64	7.38
Significance	NS	NS	NS
Parity			
2	9.35	1.78	5.75
3	11.65	1.52	8.84
Significance	0.03	NS	< 0.0001
SEM	0.71	0.15	0.37

a) values are least square means

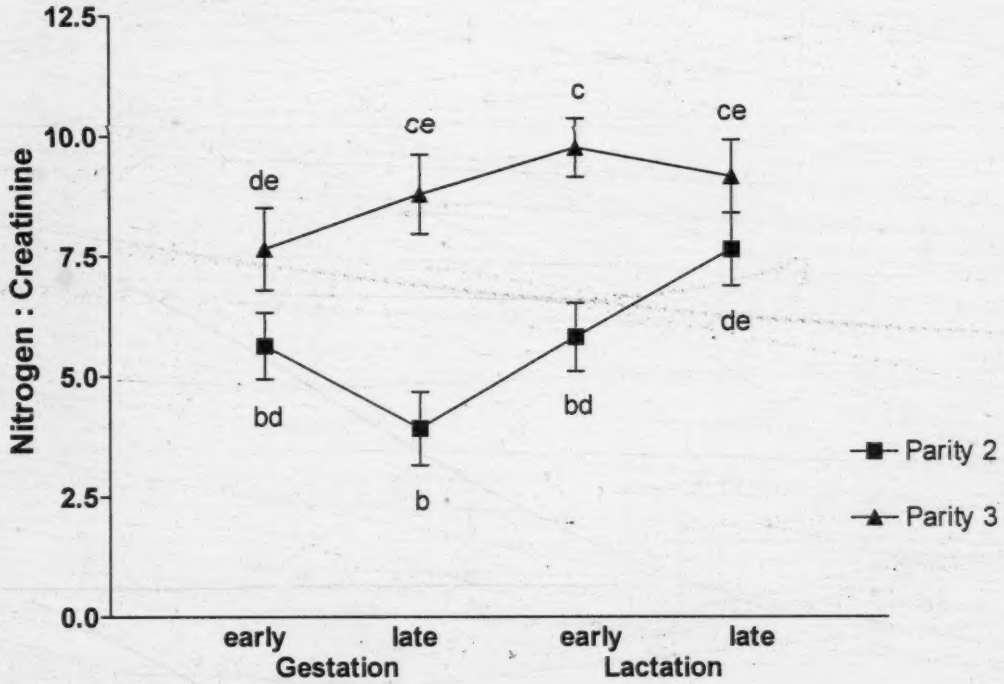
A significant three-factor interaction among physiological state, stage, and parity on the nitrogen: creatinine ratio was observed (Table 5.5.2, Figure 5.5.1). Relative nitrogen excretion was numerically lower during the second parity, compared to parity three, for each measurement point, however it was only significant during late gestation (3.92 vs. 8.79) and early lactation (5.81 vs. 9.76; $p < 0.05$). Nitrogen excretion numerically decreased from early gestation to late gestation in parity 2 (5.63 vs. 3.92; $p = 0.1$), but increased in parity 3 (7.65 vs. 8.79). An opposite relationship was demonstrated in lactation, with numerical increases in relative N excretion from early to late lactation in parity 2 (5.81 vs. 7.64), but slightly reduced relative nitrogen excretion in parity 3 (9.76 vs. 9.16).

Table 5.5.2 Interaction among parity, physiological state (gestation or lactation) and stage (early or late) on nitrogen: creatinine ratio in urine [a]

Phys	Stage	Parity 2	Parity 3
Gestation	Early	5.63 [bd]	7.65 [de]
	Late	3.92 [b]	8.79 [ce]
Lactation	Early	5.81 [bd]	9.76 [c]
	Late	7.64 [de]	9.16 [ce]

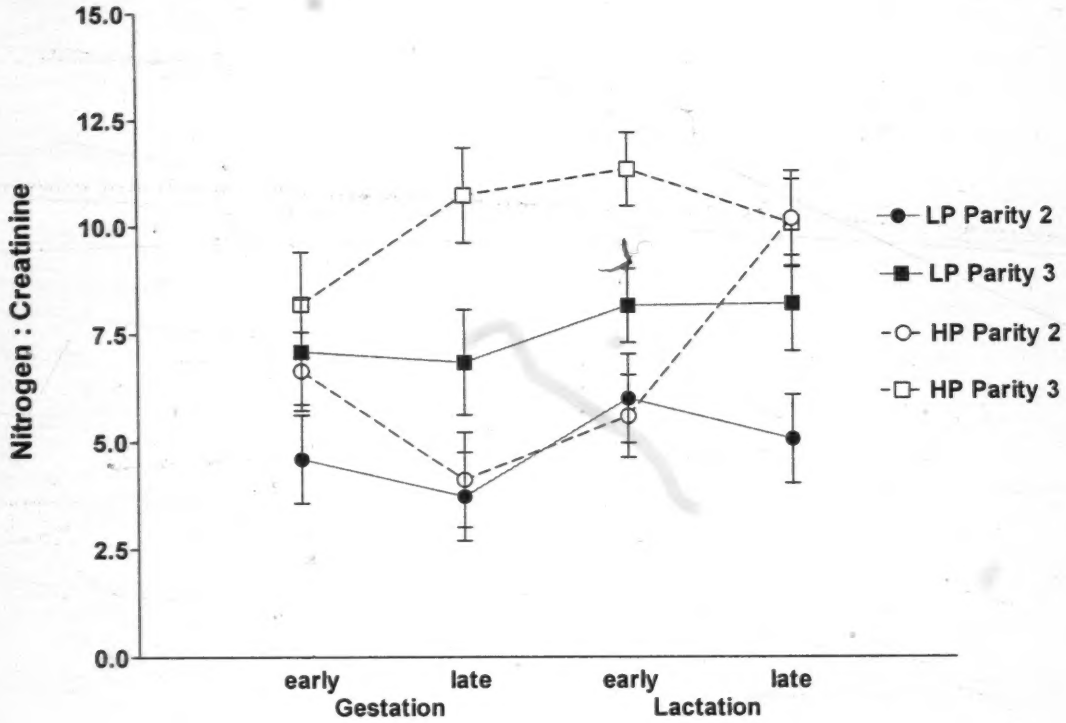
Three-factor interaction significance p = 0.014, SEM 0.75
a) values shown are least square means
b-e) means sharing a common letter are not significantly different (p > 0.05)

Figure 5.5.1 Interaction among physiological state, parity and stage on urinary nitrogen: creatinine ratio [a]
a) values shown are least square means



Additionally, a four-factor interaction among diet, parity, physiological state and stage was observed for the nitrogen: creatinine ratio (Figure 5.5.2; $p = 0.009$). Relative nitrogen excretion of LP sows was numerically higher for all measurement periods in the third parity, and statistically higher for early lactation, compared to parity 2 ($p < 0.05$). The pattern of nitrogen excretion was similar for both parities. Nitrogen excretion of HP sows was higher for late gestation and early lactation in parity 3 ($p < 0.05$), but not early gestation or late lactation, when relative nitrogen excretion was similar across parities. The pattern of response of the HP sows differed between the two parities. Nitrogen excretion decreased, then increased as the second parity progressed, whereas N excretion increased, then decreased through parity 3. During parity 2, LP sows exhibited numerically lower nitrogen excretion for early and late gestation, and statistically lower excretion during late lactation ($p < 0.05$), compared to HP sows. Conversely, nitrogen excretion of LP sows was numerically higher than that of HP sows during their second parity early lactation. During their third parity, LP sows exhibited significantly lower nitrogen excretion at late gestation and early lactation ($p < 0.05$), but not early pregnancy and late lactation, although both were numerically lower.

Figure 5.5.2 Interaction among diet, parity, physiological state, and stage on the nitrogen: creatinine ratio [a]
a) values shown are least square means



5.5.2 Plasma Amino Acid Profiles

Plasma was obtained from sows selected for deuterium oxide measurements (n=12), and, because there was sufficient quantity for both analyses, plasma was additionally analysed for amino acid content. Because D_2O measurements were only conducted during the second parity, plasma amino acid concentrations were determined in second parity sows only. Stage of gestation or lactation (early vs. late) did not affect any of the plasma amino acids measured ($p > 0.1$), and will not be discussed further. Dietary treatment significantly affected the plasma concentrations of several amino acids (Table 5.5.3). Isoleucine, leucine, valine, and tyrosine concentrations were significantly higher in the plasma of HP sows ($p < 0.02$), and arginine ($p = 0.10$), phenylalanine ($p = 0.07$) and tryptophan ($p = 0.08$) tended to be higher. Conversely,

plasma concentrations of alanine, hydroxyproline, and glycine were significantly higher ($p < 0.02$), and taurine tended ($p = 0.07$) to be higher in the plasma of LP sows. Physiological state also significantly affected several plasma amino acid concentrations. Concentrations of histidine, isoleucine, leucine, phenylalanine, valine, glutamine, proline, tyrosine, and the total sum of amino acids were higher in the plasma of lactating sows ($p < 0.05$). In contrast, the lysine concentration was lower ($p < 0.0001$), and citrulline and taurine concentrations tended to be lower ($p = 0.08$; $p = 0.09$, respectively) in the plasma of lactating sows. It is noteworthy that the dietary treatment did not significantly ($p > 0.1$) affect the plasma concentrations of lysine, methionine, and threonine.

Table 5.5.3 Effect of diet and physiological state on plasma amino acids (μM/L) [a]

	Diet		Physiological state		Significance		
	HP	**LP**	**Gestation**	**Lactation**	**Diet**	**Phys**	**SEM**
Indispensable							
Arginine	112.4	92.9	111.9	93.3	0.1	NS	8.38
Histidine	50.4	56.2	41.0	65.6	NS	0.0004	4.47
Isoleucine	127.1	89.3	90.8	125.7	0.0002	0.0005	6.53
Leucine	153.4	110.8	117.4	146.9	0.0004	0.01	7.82
Lysine	90.8	93.4	117.4	66.8	NS	<0.0001	8.04
Methionine	34.2	39.1	34.2	39.1	NS	NS	4.90
Phenylalanine	76.7	64.0	59.7	81.0	0.07	0.003	4.79
Threonine	122.9	132.9	128.1	127.8	NS	NS	9.08
Tryptophan	290.8	204.5	223.8	271.4	0.08	NS	34.23
Valine	330.0	238.8	260.0	308.8	0.0001	0.03	15.05
Dispensable							
Alanine	251.67	355.2	287.6	319.3	0.0002	NS	18.02
Aspartate	10.2	11.0	10.8	10.4	NS	NS	0.92
Citrulline	99.7	96.5	107.8	88.4	NS	0.08	7.65
OH-proline	30.1	40.6	34.2	36.5	0.006	NS	2.54
Glutamate	198.5	234.3	219.6	213.2	NS	NS	16.06
Glutamine	945.8	1003.3	681.7	1267.3	NS	<0.0001	58.58
Glycine	592.5	739.2	676.3	655.4	0.02	NS	40.69
Proline	406.2	431.7	317.9	520.0	NS	<0.0001	26.69
Serine	101.1	111.1	102.5	109.7	NS	NS	7.04
Taurine	98.5	125.9	125.1	99.3	0.07	0.09	10.37
Tyrosine	160.0	120.0	96.4	183.6	0.01	<0.0001	10.96
SUM	4874.8	4749.5	4329.1	5295.1	NS	0.006	236.56

a) values shown are least square means

Diet by physiological state interactions were observed ($p < 0.05$) for plasma lysine, valine, isoleucine, alanine and glutamate concentrations, and approached significance ($p = 0.06$) for leucine (Table 5.5.4). Interactions and differences were not significant for most amino acids, however, they are included in the table to assist in the interpretations of observed patterns in plasma amino acid concentrations. Of interest, was the lack of significant differences for the potentially limiting amino acids: threonine, methionine and tryptophan. Plasma lysine was not different between HP and LP sows during gestation or lactation. The concentration of lysine was not different between gestation and lactation for HP sows, but was higher in gestation, compared to lactation, in LP sows. Plasma isoleucine, leucine, and valine concentrations were not affected by diet during gestation, but were higher for HP sows during lactation ($p < 0.05$). The plasma concentrations of these amino acids were not different between gestation and lactation in LP sows ($p < 0.05$). Plasma alanine, and glutamate concentrations were not different between diets during gestation ($p > 0.05$). Alanine in HP sows did not differ between gestation and lactation, whereas plasma alanine in LP sows was lower during gestation, compared to lactation, and lactation alanine concentration in LP sows was significantly higher than HP sows ($p < 0.05$). Conversely, plasma glutamate concentration was lower during gestation, than lactation ($p < 0.05$) for HP sows, but did not differ between gestation and lactation for sows fed the LP diet.

Table 5.5.4 Interaction between diet and physiological state on some plasma amino acids (μM/L) [a]

	Gestation		Lactation			
	HP	LP	HP	LP	SEM	Interaction significance
Alanine	263.5 [bd]	311.7 [b]	239.9 [d]	398.8 [c]	25.46	0.04
Glutamate	235.6 [b]	203.5 [bc]	161.5 [c]	265.0 [b]	22.69	0.005
Isoleucine	99.1 [b]	82.4 [b]	155.2 [c]	96.2 [b]	9.23	0.03
Leucine	128.2 [b]	106.6 [b]	178.7 [c]	115.0 [b]	11.05	0.06
Lysine	102.9 [bd]	131.9 [b]	78.7 [cd]	54.9 [c]	11.36	0.03
Valine	283.1 [b]	237.0 [b]	377.0 [c]	240.7 [b]	21.27	0.04
Arginine	118.6	105.3	106.2	80.4	11.84	0.60
Aspartate	11.1	10.4	9.2	11.6	1.30	0.23
Citrulline	101.3	114.3	98.1	78.6	10.82	0.14
Glutamine	704.5	658.9	1187.1	1347.6	82.78	0.22
Glycine	627.5	725.2	557.5	753.2	57.50	0.40
Histidine	40.7	41.4	60.2	71.0	6.32	0.43
Methionine	29.1	39.4	39.4	38.9	6.91	0.46
OH-proline	31.5	37.0	28.8	44.3	3.58	0.17
Phenylalanine	61.6	57.9	91.8	70.2	6.77	0.19
Proline	318.3	317.6	494.1	545.8	37.71	0.49
Serine	102.6	102.4	99.6	119.9	9.95	0.31
Taurine	117.9	132.4	79.2	119.5	14.65	0.39
Threonine	119.2	137.0	126.7	128.8	12.84	0.55
Tryptophan	238.1	209.6	343.5	119.3	48.39	0.24
Tyrosine	105.8	87.0	214.2	153.0	15.49	0.18
SUM	4307.9	4350.3	5191.1	5399.2	334.28	0.81

a) values shown are least square means

b-d) means within rows not sharing letters are significantly different ($p < 0.05$)

5.6 Energy Expenditure

Measurements of gas exchange and heat production by the sows were initially analyzed with diet, parity, physiological state, and stage as main effects (Table 5.6.1). Dietary treatment significantly affected gas exchange and heat production, with sows fed the LP diet exhibiting significantly reduced carbon dioxide excretion (6.6%), consumption of oxygen (8.3%) and total heat production expressed on a per day (8%) or per metabolic live weight basis (6%; $p < 0.005$). The respiratory quotient (RQ) was not different between HP and LP sows, however ($p > 0.1$). Physiological state strongly influenced energy expenditure of the sows (without piglets). Sows consumed less oxygen, excreted lower amounts of CO_2 and produced less heat during gestation ($p < 0.0001$), compared to lactation. As well, the respiratory quotient of the gestation diet was lower than that of the lactation diet (0.83 vs. 0.91; $p < 0.0001$). Across physiological states, stage only affected RQ ($p = 0.04$), although heat production per kg of metabolic live weight tended to be lower during the later stage of gestation/ lactation ($p = 0.07$). Parity significantly influenced CO_2, O_2, heat production and respiratory quotient. Second parity sows exhibited lower carbon dioxide production, oxygen consumption, daily heat production and RQ ($p \leq 0.05$) than third parity sows. Conversely, heat produced per unit metabolic body weight tended ($p = 0.08$) to be lower during third parity.

Table 5.6.1 Effect of diet, physiological state, stage and parity on gas exchange, heat production and respiratory quotient of sows [a]

	CO_2 production (g/d)	O_2 consumption (g/d)	Heat production (kJ/d) [b]	Heat production kJ/ $BW^{0.75}$/d	Respiratory Quotient (RQ)
Diet					
HP	3820.4	3209.1	48770	864.8	0.86
LP	3569.6	2940.7	44873	812.1	0.88
Significance	0.003	0.0002	0.0002	0.004	NS
Phys					
Gestation	2941.0	2591.7	38993	715.8	0.83
Lactation	4449.0	3558.1	54650	961.0	0.91
Significance	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Stage					
Early	3648.2	3076.1	46706	854.8	0.86
Late	3741.8	3073.7	46937	822.0	0.89
Significance	NS	NS	NS	0.07	0.04
Parity					
2	3448.8	3007.3	45343	854.3	0.83
3	3941.2	3142.5	48300	822.5	0.91
Significance	<0.0001	0.05	0.005	0.08	<0.0001
SEM	59.4	49.8	727.1	12.8	0.009

a) values shown are least square means

b) calculated according to the formula M (kJ) = 16.18* V_{O2} + 5.02* V_{CO2}

A significant interaction between physiological state and parity on sow gas exchange and daily heat production was observed (Table 5.6.2). The interaction between stage and parity on heat production per unit of metabolic body weight, or on the respiratory quotient was not significant. Carbon dioxide production was higher during lactation, for both parities ($p < 0.05$), and excretion of carbon dioxide was greater in the third parity, for both gestation and lactation ($p < 0.05$). Oxygen consumption during gestation was not influenced by parity (2607.5 vs. 2576.0 g/d; $p > 0.05$). Consumption of oxygen during lactation was higher than gestation consumption, and was lower in parity two than parity three (3407.1 vs. 3709.0 g/d; $p < 0.05$).

Daily total heat production followed a similar pattern as O_2 consumption. Heat production was not influenced by parity during gestation, but heat production in lactation was greater than gestation heat production, and increased with increased parity ($p < 0.05$).

Table 5.6.2 Interaction between physiological state and parity on overall sow gas exchange and heat production [a]

	Gestation		Lactation			
	Parity					
	2	3	2	3	SEM	Interaction significance
CO_2 production (g/d)	2814.2 [b]	3067.7 [c]	4083.3 [d]	4814.7 [e]	84.0	0.005
O_2 consumption (g/d)	2607.5 [b]	2576.0 [b]	3407.1 [c]	3709.0 [d]	70.3	0.02
Heat production (kJ/d)	38840 [b]	39146 [b]	51847 [c]	57453 [d]	1028.2	0.01
Heat production kJ / kg $^{0.75}$ / day	744.1	687.6	964.6	957.4	18.2	0.18

a) values shown are least square means
b-e) means sharing letters within a row are not significantly different ($p<0.05$)

A significant interaction between physiological state and stage on heat produced per metabolic kg of body weight was observed (Table 5.6.3; $p = 0.05$). Heat production per unit metabolic weight was higher in early gestation, compared to late gestation ($p < 0.05$). However, no difference in heat production was observed between early and late lactation. Heat production was significantly greater during lactation, in both periods ($p < 0.05$).

Table 5.6.3 Interaction between physiological state and stage on daily heat production per unit of metabolic body weight [a]

	Gestation		Lactation		
	Early	Late	Early	Late	SEM
Heat production kJ / kg $^{0.75}$ / d	749.7 [b]	682.0 [c]	960.0 [d]	962.0 [d]	0.46

Interaction significance = 0.05
a) values shown are least square means
b-d) means with different letters are significantly different ($p<0.05$)

Because there were distinct feeding levels for gestation and lactation, the effect of feed intake could not be separated from diet, for the overall data set. Although feed intake during gestation was similar for the two dietary treatments, LP sows consumed less feed than HP sows in lactation (Table 5.1.6). In order to evaluate the effect of diet, separate from feed intake, on gas exchange, and heat production, data was separated into gestation and lactation, and reanalyzed. This also allowed for the evaluation of piglet effects on energy expenditure. The main effects evaluated were diet, parity and stage, with feed intake used as a covariate during both gestation and lactation.

For sows fed the LP diet during gestation, carbon dioxide production (2861.2 vs. 3024.2 g/d; $p = 0.01$; Table 5.6.4), oxygen consumption (2508.4 vs. 2678.0 g/d; $p = 0.01$), and heat production expressed as total heat production (6%; $p = 0.007$) or heat produced per kilogram of metabolic body weight (697.6 vs. 734.9 kJ/ kg $BW^{0.75}$/d; $p = 0.03$) were significantly lower, compared to sows fed the HP diet. Stage of gestation significantly affected CO_2 production and heat production per kg metabolic weight, but not oxygen consumption or total heat production. Sows excreted less carbon dioxide during early gestation, compared to late gestation ($p = 0.009$). In contrast, heat production per unit of metabolic body weight was higher in early, compared to late gestation (746.1 vs. 686.3 kJ/ kg $BW^{0.75}$/d; $p = 0.0005$). Regardless of dietary treatment, carbon dioxide excretion and the respiratory quotient of the sows were significantly lower in the second parity ($p < 0.0001$). No parity differences were observed for oxygen consumption and heat production (total or metabolic) between LP and HP sows ($p > 0.1$).

Table 5.6.4 Effect of diet, stage and parity on the gas exchange, heat production and respiratory quotient of sows during gestation

	CO_2 production (g/d) [a]	O_2 consumption (g/d) [a]	Heat production (kJ/day) [a]	Heat production kJ/ $BW^{0.75}$/d [a]	Respiratory Quotient (RQ) [b]
Diet					
HP	3024.2	2678.0	40245	734.9	0.83
LP	2861.2	2508.4	37784	697.6	0.84
Significance	0.01	0.01	0.007	0.03	NS
Stage					
Early	2860.2	2564.7	38453	746.1	0.82
Late	3025.2	2621.6	39576	686.3	0.85
Significance	0.009	NS	NS	0.0005	NS
Parity					
2	2774.0	2574.3	38340	730.4	0.79
3	3111.4	2612.1	39689	702.0	0.87
Significance	<0.0001	NS	NS	NS	<0.0001
SEM	44.5	47.6	638.6	11.8	0.01

a) values shown are least square means adjusted for feed intake as a covariate
b) RQ values not adjusted for feed intake

There was a significant interaction ($p = 0.05$) between diet and parity on excretion of carbon dioxide by gestating sows (Table 5.6.5). For both dietary treatments, CO_2 excretion increased with increasing parity. Excretion of carbon dioxide was similar for the two dietary treatments during parity 2 ($p > 0.05$), but was significantly higher for HP sows during parity 3, than parity 2 ($p < 0.05$).

Table 5.6.5 Interaction between diet and parity on carbon dioxide production in gestating sows [a]

	Parity	
	2	3
Diet		
HP	2794.6 [bc]	3253.8 [d]
LP	2753.3 [c]	2969.0 [b]

SEM = 63.67, significance of two factor interaction = 0.05
a) values shown are least square means adjusted for feed intake as a covariate
b-d) means with different letters are significantly different ($p < 0.05$)

Gas exchange of lactating sows, without their piglets, was measured to account for the effect of litter on gas measurements (Table 5.6.6). Sows fed the low protein diet displayed lower oxygen consumption, daily heat production, and respiratory quotient ($p < 0.05$), than sows fed the high protein diet. Carbon dioxide excretion and heat produced per kg metabolic body weight were not affected by dietary treatment (LP, 4359.6 vs. HP, 4535.0 g/d, CO_2; 936.3 vs. 984.4 kJ/kg $BW^{0.75}$/d; $p > 0.1$). Stage of lactation did not influence carbon dioxide production, O_2 consumption, heat production (total or metabolic) or RQ ($p > 0.1$). Parity significantly influenced CO_2 production, heat production, and the respiratory quotient, but not O_2 consumption, or heat production per unit of metabolic body weight. Sows exhibited lower carbon dioxide production and RQ during second parity ($p < 0.005$). Additionally, total heat production was higher during parity three than during parity two ($p = 0.05$).

Table 5.6.6 Effect of diet, stage and parity on gas exchange, heat production and respiratory quotient of sows during lactation [a]

	CO_2 production (g/d)	O_2 consumption (g/d)	Heat production (kJ/day)	Heat production kJ/ $BW^{0.75}$/d	Respiratory Quotient (RQ)
Diet					
HP	4535.0	3699.9	56575	984.4	0.89
LP	4359.6	3412.1	52653	936.3	0.93
Significance	NS	0.02	0.04	NS	0.04
Stage					
Early	4533.8	3632.4	55763	975.2	0.91
Late	4360.8	3479.6	53465	945.6	0.92
Significance	NS	NS	NS	NS	NS
Parity					
2	4191.9	3460.7	52782	976.2	0.88
3	4702.7	3651.3	56445	944.6	0.94
Significance	0.0009	NS	0.05	NS	0.003
SEM	101.6	87.5	1286	22.8	0.01

a) values are least square means adjusted for feed intake as a covariate

Gas exchange and heat production during lactation were calculated for the sow with her litter (Table 5.6.7). Gas exchange and sow and litter heat production values were adjusted using feed intake and number of piglets nursing as covariates to account for differences in lactation feed intake and number of piglets nursing. There was a trend ($p = 0.1$) for LP fed sows and their litters to excrete less carbon dioxide. Oxygen and heat production of the sow and litter were significantly lower in the LP group. Calculated heat production of the piglets (as kJ/piglet/day) was not affected by the sow's diet, indicating that the changes in heat production and oxygen consumption were due entirely to differences in metabolism by the sow. Gas exchange, and total heat production of the sow with her litter, and heat production per piglet were significantly affected by stage of lactation ($p < 0.0001$). CO_2 production, O_2 consumption and heat production of the sow and litter, and heat production of the piglets was greater during late lactation, compared to early lactation. When heat produced by the piglet was expressed on a metabolic weight basis, no differences between early and late lactation were observed, although heat production during late lactation was numerically lower (940.5 vs. 865.2 kJ/kg $BW^{0.75}$/d). Carbon dioxide excretion was significantly affected by parity ($p = 0.007$), with sows excreting greater quantities of CO_2 in the third parity. Oxygen consumption and heat production by the sow and litter were not influenced by parity. Trends for lower heat production per piglet, expressed on a daily total ($p = 0.07$) or metabolic weight basis ($p = 0.08$), with increasing parity were observed.

Table 5.6.7 Effect of diet, stage and parity on gas exchange and heat production of the sow and her litter during lactation

	Sow and litter CO_2 (g/d) [a]	Sow and litter O_2 (g/d) [a]	Sow and litter Heat (kJ/d) [a]	Heat/piglet (kJ/d) [b]	Heat/piglet (kJ/BW $^{0.75}$) [b]
Diet					
HP	6482.1	5391.6	82100	2536.4	905.4
LP	6315.5	5083.5	77959	2467.4	900.2
Significance	0.1	0.001	0.002	NS	NS
Stage					
Early	6113.3	4990.7	76302	2020.3	940.5
Late	6684.3	5484.3	83758	2983.6	865.2
Significance	<0.0001	<0.0001	<0.0001	<0.0001	NS
Parity					
2	6257.1	5269.0	80024	2669.9	965.1
3	6540.5	5206.0	80035	2333.9	840.5
Significance	0.007	NS	NS	0.07	0.08
SEM	69.8	64.8	891	129.2	49.3

a) values shown are least square means adjusted for feed intake and number of piglets
b) values shown are unadjusted least square means

5.7 Body Composition by Deuterium Oxide

Analysis of plasma samples for deuterium oxide dilution, to determine body composition, is currently not available.

5.8 Economic Analysis

Cost per tonne of feed was calculated using ingredient prices published biweekly by Alberta Agriculture (Bi-weekly Bulletin, Agriculture Canada website; http://www.agr.gc.ca/policy/winn/biweekly/e/arche/archbbe.htm). Synthetic amino acid prices were determined on a constant pricing assumption, and with lysine and threonine prices linked to soybean meal price in a fixed ratio, based on the soybean vs. threonine or lysine prices on November 5, 2001 (ratio at end of study; threonine = 21.47; lysine = 11.066). Average cost for the two gestation diets was similar ($p > 0.1$), however the HP gestation diet averaged $1.15 less per tonne with constant AA pricing and $0.72 less with variable AA pricing (Table 5.7.1). Average cost of the lactation diets was also similar ($p > 0.1$), however, the LP lactation diet averaged $1.37 (constant AA pricing) or $1.89 per tonne (variable AA pricing) less.

Table 5.7.1 Average feed cost for the experimental period

	Feed Cost [a]		Feed Cost [b]	
	Gestation	Lactation	Gestation	Lactation
Diet				
HP	$176.70	$209.49	$176.70	$209.49
LP	$177.85	$208.12	$177.42	$207.60
Significance	NS	NS	NS	NS
SEM	$2.66	$2.27	$2.68	$2.31

a) cost per tonne of feed, calculated biweekly from published ingredient prices, with lysine and threonine price constant

b) cost per tonne of feed, calculated biweekly from published ingredient prices, with lysine and threonine prices maintained in a fixed ratio to soybean meal price

Feed cost per sow per reproductive cycle was determined using average feed intakes of each of the four diets during the experimental period. Feed cost was determined with constant amino acid prices and for variable pricing (Table 5.7.2).

Feed cost with constant amino acid pricing is provided first. The cost to feed a sow for one production cycle was similar for the two diet treatments (Table 5.7.2), however pricing tended to favor the LP diet for both variable ($72.86/sow/cycle vs. $75.51/sow/cycle; p = 0.07) and constant amino acid pricing ($73.04/sow/cycle vs. $75.51/sow/cycle; p = 0.08). Revenue from piglets was calculated from the number of piglets weaned and the average weight of piglets weaned at 21+ days (nursed piglets). Revenue from piglets was not different for the two diet treatments (p = 0.09), but tended to favor piglets weaned from sows fed the HP diet, due to slight differences in number of piglets weaned, and nursed piglet weights (Table 5.1.5). Margin over feed cost was not different between the diet treatments (p > 0.1), regardless of how feed cost was calculated. However, the HP diets resulted in an economic benefit of $19.82 (variable amino acid cost) or $20.00 (constant amino acid cost) compared to the LP diets, over the course of one productive cycle.

Table 5.7.2 Feed cost, piglet revenue and margin over feed cost of average weaned piglets for variable and constant amino acid pricing

	Diet			
	High protein	**Low protein**	**Significance**	**SEM**
Variable AA cost				
Feed cost/ sow [a]	$75.51	$72.86	0.07	1.00
Piglet earnings	$385.89	$363.43	0.09	9.20
Margin/ Feed cost	$310.39	$290.57	NS	9.13
Constant AA cost				
Feed cost/ sow [a]	$75.51	$73.04	0.08	0.99
Piglet revenue	$385.89	$363.43	0.09	9.20
Margin / feed cost	$310.39	$290.39	NS	9.13

a) feed cost per sow calculated using least square means feed intake

6.0 DISCUSSION

In this study, we wished to examine the effects of low protein diets on a variety of sow performance and metabolic characteristics. To that end, several hypotheses were proposed, and evaluated during the study period, in order to provide a comprehensive picture of what occurs in sows fed low protein, amino acid supplemented diets. Our specific objectives were to examine the effect of feeding low protein diets during gestation and lactation on:

1) Sow performance, feed intake, litter characteristics (numbers born and weaned, piglet weights, growth rates) and reproductive adequacy (wean to estrus interval, percent return to service, conception rate, farrowing rate)

2) Changes in body weight and the composition of weight changes

3) Possible nutritional carry-over effects from one parity to the next

4) Sow milk production and composition

5) Diet digestibility

6) Urinary nitrogen excretion and plasma amino acid profiles

7) Energy metabolism of sows during gestation and lactation

and

8) To determine the economic viability of feeding low protein, amino acid supplemented diets in gestation and lactation

6.1 Effect of Low Protein, Amino Acid Supplemented Diets on Animal Performance

In order to provide sows nutrient levels closer to their amino acid and energy requirements, we must understand the effect of nutrient supply on sow performance. Performance characteristics include the amount of weight gained during gestation, litter size, piglet weights and growth rate, sow weight changes during lactation, and the ability of sows to rebreed quickly, and successfully after weaning. Additionally, knowledge of how dietary

manipulations affect body composition of the producing sow is very important, because body composition can influence feed intake (Eissen et al, 2000) and thus, performance during lactation. The simplest method of determining the effect of dietary treatments on body composition is to measure growth rate of the sow; this is easily achieved by repeatedly measuring live weight and backfat depth over a predetermined period of time. Because all these criteria are non-invasive, and are routine procedures in many facilities, they can be examined repeatedly on individual animals to acquire a comprehensive picture of what occurs in sows fed low protein, amino acid supplemented diets throughout the productive lifetime of the animal.

The performance averages of the sows selected for intensive measurements were similar to the entire group of animals, i.e. the patterns observed were the same, indicating that the response to diet and parity for the subset of sows was not different from that of the entire group. Differences observed to be significant in the extensive sows did not always reach significance for the intensive sows, because the smaller number of observations resulted in a larger error term (Tables 5.1.7 to 5.1.11). Therefore, this discussion will focus on the overall effects of diet and parity, without separating extensive and intensively studied sows.

6.1.1 Gestation Performance

Data from sow performance during gestation agrees with our hypothesis that low protein, amino acid supplemented diets will support performance similar to that of sows fed a conventional intact protein diet. Gestating LP sows consumed similar amounts of feed, but, on average, 68.6 grams less crude protein and 2.5 MJ less digestible energy per day, compared to HP sows (Table 5.1.6). The reduction in crude protein intake was planned, however diets were originally formulated to supply similar digestible and metabolizable energy. The lower intake of digestible energy resulted from variations in energy content of dietary ingredients, from table values (NRC, 1998), and lower apparent digestibility of energy in the low protein gestation diet, compared to the high protein diet. LP sows, however, gained similar amounts of body weight

and backfat during gestation as HP sows (Table 5.1.2), indicating that the low protein gestation diet supplied adequate energy and amino acids to support gestation. Additionally, the lack of differences in backfat depth suggests that LP sows consumed a similar amount of net energy as HP sows.

The digestibility of nutrients in our gestation and lactation diets was determined by adding an indigestible marker to the feed. Satisfactory markers are completely indigestible and unabsorbable (Maynard and Loosli, 1969), and include substances such as ferrous oxide and chromic oxide. By determining the concentration of indigestible marker in feed and feces, and the concentration of the nutrient(s) of interest in feed and feces, digestibility of the nutrient can be calculated (Maynard and Loosli, 1969). This procedure does not require knowledge of feed intake or fecal output, making it ideal for determining digestibility in studies where complete fecal collection is not possible. For this study, we utilized chromic oxide as our marker.

The digestibilities of crude protein and energy were lower for the low protein gestation diet (Table 5.4.1). Several studies have observed a decrease in crude protein digestibility when feeding a low protein, amino acid supplemented diet to growing pigs (Just, 1982; Noblet et al, 1987; Kerr and Easter, 1995; Heger et al, 1997), and related it to the negative effect of endogenous nitrogen losses on digestibility of nitrogen with low protein diets. The amount of endogenous protein is proportional to the amount of dry matter in the diet, and thus will account for a greater proportion of the nitrogen excreted when feeding a low protein diet, compared to a high protein diet. Therefore, it will exert a greater negative effect on protein digestibility in a low protein diet than in a high protein diet (Just, 1982). Alternatively, the decrease in crude protein digestibility may be due to the decrease in the soybean meal content of the LP diet, compared to the HP diet (Table 4.1.1). The amino acids in soybean meal are more digestible than the amino acids in grains (NRC, 1998), and the soybean meal content of the LP gestation diet was much lower than that in the HP diet. However, other growing pig studies (Le Bellego et al, 2001; Lee et al, 2001; Gomez et al, 2002), as well as those specifically examining

producing sows (Cuaron et al, 1984; Kerr and Easter, 1986), have not observed differences in protein digestibility with low protein diets, and several of these studies considerably reduced soybean meal content in their low protein diets (Cuaron et al, 1984; Lee et al, 2001; Gomez et al, 2002).

Unlike our study, other studies (Le Bellego et al; 2001; Gomez et al, 2002) have found no effect of reducing crude protein on energy digestibility. In a second experiment, Gomez et al (2002) observed increased energy digestibility in a low protein grower diet, and speculated that the increase might be due to the different proportions of grain and soybean meal in the two diets. However, energy digestibility is a reflection of the digestibility of nutrients in the diet, especially protein and fat, and in that study the nutrient digestibilities were not influenced by diet composition, whereas the crude protein digestibility in our study was lower in the LP gestation diet.

The observed reduction in apparent energy digestibility in our study may have been due to the large decrease in soybean meal content, because the metabolizable energy content of soybean meal is higher than that of wheat or barley (NRC, 1998). Additionally, tallow was not included in the LP gestation diet, but was present in the HP diet (Table 4.1.1). Tallow is more easily digested than grains or protein sources, providing a greater quantity of digestible energy per unit than other nutrient sources (NRC, 1998). The lower digestibility of energy in the LP diet resulted in gestating LP sows having a lower intake of digestible energy, at the same level of feed intake, compared to sows fed the HP diet.

Daily intake of total amino acids was calculated from mean daily feed intakes during gestation, for each of the dietary treatments. These intakes were then compared against the amino acid requirements predicted by the NRC (1998) model, based on actual performance of our sows. Sows from both diet treatments consumed more than sufficient amino acids during gestation to meet their requirements (NRC, 1998), in both parities (Table 5.3.1, Table 5.3.2). This was partially due to the higher than expected crude protein contents of the diet. Diets were

initially formulated to contain 14.76% crude protein (HP diet) and 11.98% crude protein (LP diet). However, the crude protein content of several ingredients was higher than originally expected, increasing the crude protein of the HP diet to 16.25% CP, and the LP diet to 13.52% CP (Table 4.1.1). Diets were formulated to accommodate a 125 kg sow, because the University of Alberta's swine herd consisted primarily of gilts, however, sows began their second parity gestation at approximately 164 kg, and their third parity gestation at 184 kg.

Sows from both dietary treatments experienced considerable weight gain (sow plus conceptus) during gestation (approximately 60 kg) with similar backfat increases (Table 5.1.2), indicating that both the high and low protein diet supplied adequate amino acids and energy to meet the requirements of these animals. Furthermore, sows fed the low protein diet demonstrated weight gains similar to that of HP sows, in concordance with observations from other studies (Corley et al, 1983; Cuaron et al, 1984). This evidence does not support the application to sows, of observations in growing pigs, that low protein, amino acid supplemented diets, fed infrequently (i.e. once per day), will be used less efficiently (Batterham and Murison, 1981; Batterham and Bayley, 1989). Additionally, the similarity of weight gain and backfat depth increases throughout gestation indicates that protein retention was constant between the two dietary treatments.

In accordance with the total gestation weight gains, daily weight gains during gestation were quite high; approximately 475 g/day in early gestation, increasing to 775 g/ day, or higher, during the last two weeks of pregnancy. This increase was likely indicative of the faster growth rate of the fetuses during the last trimester of gestation (Noblet et al, 1997).

Although the feed intake recommendation of Aherne and Foxcroft (2000) was used to determine the amount of feed sows should be allotted, weight gain experienced by these sows during gestation was greater than expected, resulting in our sows entering lactation at higher than expected body weight. The NRC (1998) states that energy intakes above 25 kJ ME/day will increase weight gain in gestation, above that stated in their tables. Our sows consumed

approximately 32 kJ ME/day, which may account for some of the extra weight gain. When the actual energy intakes of these gestating sows was entered into the NRC (1998) model, predicted total gestation gain was similar to the weight gain observed in this study. However, the difference between observed maternal gain (approximately 48 kg; Table 5.1.2) and that suggested by the feed intake recommendation was large. Dietary protein concentrations and digestible and metabolizable energy contents of our diets were similar to the values suggested by the feeding schedule. At a daily intake of 2.2 kg of a 3 Mcal ME/kg diet, according to the feeding schedule, sows were expected to gain 17.5 kg of maternal weight and 1.75 mm of backfat. Our sows gained approximately 48 kg of maternal body weight during gestation. A large portion of the greater gain appeared to be maternal protein gain, rather than fat, because sows only gained 2 mm of backfat during gestation (Table 5.1.2), to average 19 mm of backfat at farrowing. The large weight gains observed, with a moderate gain in backfat suggests that the feed allocation table used by the University of Alberta Swine Research and Technology Centre does not accurately account for the growth potential of the current genetic stock (Genex Landrace/Large White), and the feeding regimen should be revised. This does, however, emphasize the need for more accurate descriptions of the growth potential of different genotypes, and of sows in general.

The comparison of actual amino acid intake to predicted requirement (NRC, 1998) during gestation concurred with the high level of sow weight gain observed during this period. No amino acids were limiting to sow performance (Table 5.3.1; Table 5.3.2), however, it did appear that we were overfeeding during gestation. The excess intake of amino acids was partially due to the higher than expected protein contents of the diets, and partly due to the inability of the feed allocation sheet used at the University of Alberta Swine Research and Technology Centre to estimate weight gains of gestating sows (Aherne and Foxcroft, 2000). In particular, arginine, and phenylalanine were consumed at quantities well above the requirement of the animal. From these data, we can assume that the crude protein content of the gestation

diet could be reduced further, to reduce the excess amino acids supplied, and that there is great potential to use low protein, amino acid supplemented diets during this period of production.

Plasma concentrations of amino acids reflect amino acid supply, relative to requirement. In response to increasing intake, the concentrations of amino acids in the plasma increase very slowly until the requirement for the amino acid is met, then increases more rapidly until the body's capacity to catabolize excess is exceeded, and then increase very rapidly, with further additions of amino acid (Chen et al, 1978; Wilkinson et al, 1984). Plasma amino acids were measured during the second parity only, however, these provided a picture of the adequacy of amino acid supply to meet the amino acid requirement of the animal during that parity. For those amino acids that could be examined, the interaction between diet and physiological state indicated that amino acid concentrations during gestation were not different between the dietary treatments (Table 5.5.4), even though intake of all amino acids, except lysine, was lower for LP sows (Table 5.3.1). In accordance with the amino acid intake calculations, and high level of gestation weight gains, the similarity of plasma concentrations of all measured amino acids, between the two dietary treatments (Table 5.5.4), indicated that both diets contained sufficient amino acids to meet the requirements of second parity gestating sows.

Generally, growth rate decreases as animals reach mature body weight, however, all gestating third parity sows experienced greater weight gains than during their second parity gestation (Table 5.1.3). This was likely maternal gain, because the increased gain was observed during early and mid pregnancy, when fetal growth was still minor. Indeed, sows are still actively growing through the fourth parity (Clowes, 2001). Additionally, although third parity litters contained more piglets, litter weights at farrowing were not different between the two parities. In accordance with the higher growth rate in the third parity, the excess intake of amino acids by gestating sows was greater during their third parity, suggesting that the high level of amino acid intake may have caused the higher growth rate of third parity gestating

sows. Furthermore, this indicates that either feeding regimen, or dietary nutrient supply, must be re-evaluated as sows mature.

When gestation weight gain was separated into early, and mid through late gestation gains, it was apparent that sows fed the low protein diet experienced a greater rate of weight gain during early gestation of the third parity, than HP sows. This high rate of gain in early gestation may be indicative of compensatory growth to refurbish the greater loss of body stores during lactation (O'Grady and Hanrahan, 1975), however, weight loss of second parity sows fed the low protein diet was not excessive (11.6 kg; Table 5.1.4). Interestingly, the ability of LP sows to gain weight faster than sows receiving the HP diet, at similar feed intakes, suggests that LP sows utilized dietary protein more efficiently than HP sows during early gestation, probably due to the better amino acid profile, relative to requirement, of the LP diet (Table 5.3.3).

Although the overall gain in backfat during each gestation was similar, when backfat gain during gestation was examined, it was apparent that sows did not deposit backfat similarly during the two parities (Table 5.1.2). The high rate of backfat gain and subsequent decrease in backfat as their second parity gestation progressed suggested that sows were not consuming sufficient energy in late gestation to meet their energy requirement, and were forced to mobilize backfat to supply energy for maintenance and fetal growth. It is also possible that sows were responding to a previous energy deficit, before initiation of this study, by exhibiting compensatory fat gain in early gestation, once placed on an energy adequate diet. This pattern was not observed during parity three, where sows gained similar backfat during early and late gestation, indicating that the effect observed in the second parity was unique to that time period, and that sows were not experiencing an energy deficit in parity three. These data suggest that the actual energy requirements of sows in parity two is higher than predicted by the NRC (1998) model, and greater than third parity sows.

The overall gestation data indicates that amino acid supply did not limit sow performance during gestation, but that energy available for tissue deposition may have been

limiting during late pregnancy, especially during the second parity. This energy limitation may have resulted from the large increase in sow body weight from the beginning of gestation. Larger sows require more nutrients and energy to support tissues, however, feeding level was kept constant throughout gestation. While the generous amino acid intake prevented deficiencies from occurring during late gestation, it was obvious that this level of feed intake was insufficient to supply the energy requirement of the sow during late gestation of parity two.

6.1.2 Lactation Performance

During lactation, LP sows consumed, on average, 500 grams less feed, 274 grams less crude protein, and 11.3 MJ less digestible energy per day than HP sows (Table 5.1.6). The reduction of lactation feed intake observed with the feeding of low protein, amino acid supplemented diets in this study is dissimilar from other studies (O'Grady and Hanrahan, 1975; Tokach et al, 1992b; Johnston et al, 1999; Renaudeau et al, 2001; Trombetta et al, 2001), which observed similar feed intakes between sows fed a low protein diet, and those consuming a conventional diet. The reduction of lactation feed intake observed with sows fed the LP diet was not likely due increased maternal fat stores compared to HP sows (Prunier et al, 2001), because both gestation weight gains, and backfat measurements were similar for the two feeding treatments (Table 5.1.2). Although amino acid imbalances can reduce feed intake (O'Grady and Hanrahan, 1975), the low protein lactation diet contained a good balance of amino acids, being more similar to the ideal amino acid ratio than the HP diet (Table 5.3.6).

The demand for energy usually determines feed intake, however, sows provided the low protein diet consumed less digestible energy than HP sows. Reference to net energy intake, rather than digestible energy may help to explain this. Diets reduced in crude protein, and supplemented with crystalline amino acids have higher net energy contents than complete protein diets, at similar digestible energy levels (Le Bellego et al, 2002). With the reduction in dietary protein, there is an increase in carbohydrate content, which is utilized more efficiently

than proteins, to supply energy to the body. In addition, the reduction in excess amino acids reduces the amount of dietary energy expended to catabolize them and excrete the nitrogen. Therefore the net energy content of the LP diet was probably higher than that of the HP diet, leading to lower feed intake on the LP diet, because the sows were consuming a similar amount of metabolically available energy.

The feed intake pattern of sows fed the two dietary treatments demonstrated that, although feed intake for both groups increased during lactation, sows fed the LP diet consumed less feed daily, on average (Figure 5.1.3; Figure 5.1.4). Until sows were consuming 5 kg daily, feed intake was controlled by management procedure. Examining parity effects on feed intake, we observed that, during the controlled, step-up period, feed intake was similar during the two parities. However, third parity sows subsequently increased their feed intake to a greater extent than second parity sows, probably due to increased body weight, and larger litter sizes (Table 5.1.1; Table 5.1.5; Table 5.1.10), requiring greater milk production, and thus driving sows to consume more nutrients.

As with the gestation diets, apparent digestibilities of crude protein, dry matter, energy and carbon were determined for the lactation diets. The apparent digestibility of analysed nutrients was lower for the LP lactation diet, than the HP lactation diet (Table 5.4.3). The decline in protein and energy digestibility is similar to that observed for the gestation diet, and the arguments in section 6.1.1, presented above, are equally valid for the lactation diet. That we also observed decreases in dry matter and carbon digestibility may have been due to the large decrease in soybean meal content of the low protein diet, and greater NDF content of this diet, compared to the HP lactation diet.

During periods of maximal feed intake, such as during lactation, the digestibility of nutrients in the diet will, in part, determine the level of feed intake. The digestibility of the nutrients in the diet controls feed intake, because less digestible diets will cause greater gut fill and slower passage through the gastrointestinal tract, thus reducing the amount of feed that can

be consumed. This may in part explain the lower feed intake of sows fed the low protein diet, because lower nutrient digestibilities in this diet would reduce the amount of feed that these sows could consume, compared to sows fed the high protein diet. At other times, there is generally a negative relationship between feed intake and diet digestibility (Gomez et al, 2002). The digestibility of nutrients will decrease with an increase in feed intake, due to faster transit time of the feed, which concurs with the decrease in the digestibility of crude protein and energy with the progression of lactation observed in this study. This also explains the lack of stage and parity differences during gestation, because feed intake was relatively constant throughout pregnancy, and was not greatly increased from parity two to parity three. In conjunction with this relationship, the reduced digestibility of energy in the lactation diets during the third parity, compared to parity two, was likely due to the greater feed intake in parity three. Alternately, the reduction in apparent energy digestibility, without reductions in the digestibility of other nutrients may have been due to the large number of animals in the experimental design, resulting in small differences in digestibility being statistically significant.

Daily intake of total amino acids during lactation was compared to the amino acid requirements predicted by the NRC (1998) model. Amino acid requirements were determined on a percentage basis, and on a daily intake basis. Percentage requirements are based on a set feed intake, however a variety of factors, including diet digestibility, diet composition, energy density, and amino acid balance, as well as environmental temperature, genetics, and sow performance will influence feed intake (Eissen et al, 2000). During gestation it is less important to consider daily intake of amino acids, because feed intake during this period is usually controlled to allow gestating sows to gain a predetermined amount of weight and backfat. However, during lactation feed intake is determined by the factors stated above. When our lactation diets were compared to NRC (1998) on a g/kg basis, it appeared that only lysine concentration was below the stated requirement, for both diets (when calculated after completion of the study). However, because feed intake of sows fed the LP diet was lower than

expected, these animals supposedly consumed inadequate lysine, threonine, valine, isoleucine and methionine in the second parity (Table 5.3.4), and lysine, valine and isoleucine in the third parity (Table 5.3.5), based on NRC (1998) daily amino acid requirements. The extent to which these amino acids, other than lysine, were apparently consumed below their requirement was relatively minor, such that the large majority of the sow population would not be experiencing an added amino acid deficiency. Furthermore, the variety of sow performance characteristics evaluated do not indicate that further amino acid deficiencies occurred for sows fed the low protein, amino acid supplemented diet.

Sows from both dietary treatments lost body weight and backfat during the 21-day lactation, indicating that both amino acid and energy supply was inadequate to prevent maternal tissue mobilization. The amount of weight lost by lactating sows was not large (All sows HP: 5.0 kg, LP: 8.3 kg; Intensives HP: 7.0 kg, LP: 9.7 kg), however, the occurrence of weight loss by sows, from both dietary treatments, suggested that intake of at least one amino acid was deficient, in agreement with the calculation that lysine was deficient in both the LP and HP diets (Table 5.3.4; Table 5.3.5). Additionally, lactating sows fed the low protein, amino acid supplemented diet lost approximately 3 kg more body weight than sows fed the high protein lactation diet (Table 5.1.2; Table 5.1.8). Most studies examining feeding low protein diets to lactating sows have not observed increased sow weight loss (Fandaschini et al, 1994; Johnston et al, 1999; Renaudeau et al, 2001; Trombetta et al, 2001), although one study did see increased weight loss by sows fed a low protein diet, supplemented with synthetic amino acids to match the protein content of the control diet and the NRC (1988) ideal ratio of amino acids for a lactating sow (Tokach et al, 1992b).

In our study, the greater weight loss of sows fed the LP diet was likely due to the lower feed intake of these sows during lactation, compared with HP sows. There is no evident explanation for why LP sows voluntarily consumed less feed, however, it resulted in these sows also consuming less crude protein and digestible energy. Under conditions of adequate energy

intake, the quantity of weight lost during lactation is dependent on the crude protein content of the diet (Revell et al, 1998b). However, the decrease in crude protein intake by LP sows was only 274 grams per day, and diets were formulated using the ideal protein concept and supplementation of synthetic lysine and threonine to prevent deficiencies. The extra weight loss observed for LP sows may have been the result of LP sows mobilizing maternal tissue to supply both amino acids and energy. The loss of backfat from our sows during lactation indicated that energy supply was inadequate during this period, causing them to mobilize maternal fat stores to supply energy for maintenance and milk synthesis. Each 1 mm decrease in backfat depth is associated with a 1.8 kg mobilization of adipose tissue, which equates to a 1.3 to 1.5 kg loss of fat (Whittemore and Yang, 1989). In our study, this would correspond to a 3.0 kg loss of adipose for HP sows, and a 3.4 kg adipose mobilization for LP sows.

Overall loss of body weight during lactation (both HP and LP sows) was greater in the second parity, than in the third parity (Table 5.1.2), indicating that sows experienced a greater nutrient deficit (compared to their requirement) in their second parity. Lower feed intakes observed in the second parity, compared to third parity intakes may have resulted in the greater weight loss observed (Table 5.1.6). While the amino acid requirements, according to the NRC (1998) model, were higher during the third parity, due to increased productivity and body weight, the increase in feed intake from parity two to parity three resulted in sows consuming amino acids in quantities closer to their requirement. However, the increase in feed intake was insufficient to completely prevent amino acid deficiencies from occurring during the third parity. Furthermore, amino acid intake calculations determined that sows were more deficient in amino acids during their second, versus third parity (Table 5.3.4; Table 5.3.5), which concurred with the higher weight loss observed during the second parity lactation.

Lean tissue loss is mainly associated with the adequacy of amino acid supplies to meet requirement, whereas fat tissue loss is related to the difference between energy intake and energy requirement (Noblet et al, 1998). With adequate protein intake, energy restriction during

lactation mainly affects adipose tissues (King and Dunkin, 1986; Brendemuhl et al, 1989), whereas, in a situation of energy and protein deficit, for sows with high milk production and relatively low energy intakes, both lean and fat tissues will be mobilized. The NRC (1998) model did not accurately predict weight or backfat loss of our sows during their second or third parities. Lean tissue loss was greater than the NRC (1998) model prediction, while fat mobilization was lower than predicted, for both parities, although the differences between the predicted and observed losses were not as large during parity three. These observations indicate that the NRC (1998) model does not accurately predict animal responses under conditions of energy and amino acid deficiency. As body weight and backfat losses during lactation are common in commercial herds, due to inadequate feed intake, the inability of NRC (1998) to predict weight loss may have reproductive consequences within a commercial herd, if it is used as a guideline to determine animal performance.

Losses in maternal tissue, and especially protein, have been shown to affect the ability of sows to rebreed after weaning, especially when tissue loss is large (Boyd et al, 2000; Clowes, 2001). In conjunction with the relatively low levels of weight loss in this study, and similar to other studies (Falaschini et al, 1994; Johnston et al, 1999; Renaudeau et al, 2001), differences in wean to estrus interval were not observed for either dietary treatment or parity, indicating that the low protein diet was capable of maintaining reproductive capacity over a period of two parities. Additionally, the number of animals returning to estrus after weaning, conception rate and farrowing rate were very high, indicating that the reproductive ability of these animals was optimized, and was not affected by dietary treatment.

For those amino acids that could be examined, the interaction between diet and physiological state indicated that plasma amino acids concentrations during gestation were not different between the dietary treatments (Table 5.5.4). Therefore, the significant interactions were due to differences in amino acid concentrations, between the two dietary treatments, during lactation. The decrease in plasma lysine concentration from gestation to lactation

suggests that lysine was limiting to performance during lactation. This agrees with the calculations of amino acid intake versus requirement, which also determined that lysine was limiting for both the HP and LP lactation diets. Although not significant, the degree of decrease in plasma lysine concentration was greater for LP sows, suggesting that lysine was more limiting for those sows, than for sows fed the HP diet, also in accordance with the greater weight loss of LP sows. Of the indispensable amino acids, only the branched chain amino acids, leucine, isoleucine, and valine were significantly lower in the plasma of lactating sows fed the LP diets. These amino acids, and especially valine, are utilized by the mammary gland for functions other than milk synthesis (Trottier et al, 1997), and by the muscle as energy sources (Harper et al, 1984). The lower plasma concentrations of the branched chain amino acids during lactation may have been a consequence of the inadequate dietary intake of energy, and subsequent catabolism of valine, isoleucine and leucine as an energy source for maintenance and milk production. While it could be argued that the decrease in the concentrations of these amino acids in the plasma of LP sows was due to deficiency, leucine was not consumed in deficient quantities, according to NRC (1998), and the response of valine and isoleucine in the plasma was similar to that of leucine. Furthermore, plasma valine was similar for gestation and lactation in the plasma of LP sows, suggesting that this amino acid was not limiting. This contradicted the amino acid intake calculation, relative to predicted requirement by the NRC (1998) model, which indicated that valine was limiting for LP sows during lactation.

Although plasma valine concentration in lactating LP sows was lower than in HP sows, this does not necessarily indicate that a deficiency occurred. Valine is generally found circulating in high concentrations during lactation (Trottier et al, 1997), and the decrease in plasma valine may merely be a reflection of the lower intake of valine by LP sows. Additionally, when Trottier et al. (1997) supplied valine at 0.73% of the diet to lactating sows, sows lost similar amounts of body weight as in our study (9 kg vs. 11 kg), but plasma

concentration of valine was nearly half of that observed in the present study. Therefore, it is highly unlikely that valine intake of sows fed the low protein diet was less than their requirement.

The amino acid intake calculations (Table 5.3.7) indicated that lactating second parity intensive LP sows were also deficient, based on the NRC model, in methionine, threonine, valine and isoleucine. However, the concentrations of these amino acids were not different from their respective gestation concentrations, when amino acid intake was clearly above requirements, suggesting that they were not deficient during lactation. As previously stated, the response of isoleucine was similar to plasma leucine, which was consumed in adequate quantities during lactation by sows fed the low protein diet. Additionally, plasma concentrations of threonine and methionine in LP sows were nearly identical to that of HP sows during lactation. Furthermore, the concentrations of most indispensable and dispensable amino acids in the plasma of our lactating sows were reasonably comparable to those from other studies (Wilkinson et al, 1984; Trottier et al, 1997). Consequently, it is unlikely that any of these amino acids were consumed below their required intakes. Our data, therefore suggests that the NRC (1998) model does not accurately estimate the amino acid requirements of this particular genotype of sows.

Several of the dispensable amino acids, including alanine, hydroxyproline, and glycine were higher in the plasma of sows fed the LP diet (Table 5.5.3). These three amino acids, however, were not different between gestation and lactation. Conversely, glutamine concentrations in the plasma did increase during lactation. Closer examination of plasma alanine concentrations revealed that alanine was higher in the plasma of lactating LP sows, compared to lactating HP sows, and that glutamine, and hydroxyproline followed this same pattern. Alanine and glutamine are carriers of nitrogen derived from amino acid catabolism, specifically the metabolism of branched chain amino acids in muscles. Increases of alanine and glutamine in the plasma of lactating LP sows indicated that these sows experienced greater

amino acid catabolism than HP sows. This is in accord with the greater weight loss, but similar loss of backfat, in lactating sows fed the LP diet, compared to those consuming the HP diet. This also implies a greater protein loss in LP sows, which is supported by the increase in plasma hydroxyproline, because its concentration in plasma is a reflection of protein breakdown. Rising glutamine concentrations during lactation also indicated that muscle protein (amino acid) catabolism and transport of nitrogen in the plasma was increased, compared to gestation. Similarly, increased plasma proline in lactation, compared to gestation, was likely a result of increased tissue catabolism, because proline is a major constituent of connective tissue (Kim et al, 1999). Because the dispensable amino acids follow the pattern expected under situations of muscle tissue catabolism, it is reasonable to assume that the responses observed for the indispensable amino acids also accurately reflect the metabolic state of the animal, and that of all the indispensable amino acids, only lysine was limiting performance, for both dietary treatments.

6.1.3 Summary of Changes in Sow Weight and Backfat and Carry-over Effects

By visualizing the change in weight and backfat of sows, over the course of two consecutive parities (Figure 5.1.1; Figure 5.1.2), it is evident that the sows were in a dynamic state throughout the reproductive cycle. Large gains in body weight during gestation were followed by weight loss during lactation, with a subsequent return to an anabolic state after weaning. During these periods, sows were required not only to maintain and possibly increase their own tissues, but to support their offspring, either *in utero*, or through milk production. These data suggest that the theory of a dynamic amino acid requirement during lactation, proposed by Kim et al (2001), should be extended to include gestation requirements.

Several studies have noted increased carcass fatness when growing pigs were fed low protein amino acid supplemented diets (Kerr and Easter, 1995; Lee et al, 2001). However, others have not observed differences in backfat between low protein and conventionally fed

pigs (Myer et al, 1996; Tachibana and Ubagai, 1997). During the course of the present study, no differences in sow backfat were observed between the two dietary treatments (Tables 5.1.1; Table 5.1.7). Because backfat depth of the sows was not different between the two dietary treatments at any point during the experiment, we can surmise that the diets provided similar net energy intake, despite sows on the LP diet consuming less apparent digestible energy during both gestation and lactation. The loss of backfat during late gestation of the second parity, and during lactation, however, indicated that sows from both dietary treatments consumed inadequate dietary energy to meet their requirements at these times, and mobilized fat stores to supply the deficit.

The pattern in plasma amino acids during gestation indicated that all amino acids were consumed in adequate amounts. The plasma amino acid pattern during lactation, and between gestation and lactation indicated that lysine intake was probably limiting performance during lactation, and that all of the other indispensable amino acids were consumed in more than adequate amounts. The higher concentrations of alanine glutamine and hydroxyproline in the plasma of lactating sows, and higher alanine in the plasma of lactating LP sows, compared to HP sows indicated that increased muscle protein catabolism was occurring, which confirms the interpretation from weight and backfat changes.

Sows are capable of buffering the effect of nutritional insults on the fetus for a considerable period of time (Mahan, 1977), however, deficiencies of energy or amino acids can have long-term effects on productivity. Therefore, it is important to evaluate dietary alterations over an extended period, to determine if any long-term effects occur. The lack of parity interactions on the measured sow performance characteristics indicated that feeding the low protein, amino acid supplemented diets during the second parity did not affect performance in the third parity. This observation supports one of the hypotheses of this thesis, that feeding low protein diets during one parity does not influence sow performance in the next parity.

6.1.4 Piglet Characteristics, Milk Production and Composition

6.1.4.1 Piglet Characteristics and Milk Production

The number of piglets born was not different between the two dietary treatments (Table 5.1.5; Table 5.1.10), similar to observations from other studies examining low protein diets (O' Grady and Hanrahan, 1975; Corley et al, 1983; Falaschini et al, 1994; Renaudeau and Noblet, 2001). Although the number of piglets weaned was lower for LP sows, it is unclear whether dietary treatment was truly responsible for the difference, because piglets were sold at 2 and 10 days, without regard to the dietary treatment of the sows. Piglets from sows fed the low protein diets began life slightly smaller, and tended to be lighter at weaning than piglets from HP sows (Table 5.1.5). The difference in average piglet weight increased as lactation progressed, suggesting that LP sows produced less milk than HP sows, to support litter growth. Sows fed the low protein, amino acid supplemented diet exhibited lower measured milk production (Table 5.2.1), which was supported by the piglet growth data, where piglets nursing LP sows had lighter weaning weights than those nursing HP sows, although initial nursed piglet weights were not different for the two dietary treatments (Table 5.1.5; Table 5.1.10). This observation is not supported by other studies examining low protein diets for lactating sows (Mennenga, 1986; Renaudeau and Noblet, 2001), which measured, or calculated similar milk yields for low and high protein fed sows.

The average daily weight gain of piglets nursing LP sows was lower than that of piglets nursing HP sows. Other studies examining low protein diets for lactating sows have not observed reduced piglet growth rates, or weights at birth and weaning (Falaschini et al, 1994; Johnston et al, 1999; Renaudeau and Noblet, 2001; Trombetta et al, 2001), although Johnston et al (1999) did note slightly lower growth rates with a low protein diet where threonine, tryptophan and valine were below their optimal ratio. These four studies reduced dietary crude protein between 2.6 and 4.1%, supplemented with crystalline amino acids, and maintained

digestible lysine concentrations similar to their control diets. However, all, except Johnston et al (1999), utilized many fewer animals than the present study, which may have prevented some differences in performance from becoming significant. Also, none of the previous studies have evaluated two consecutive lactations. Therefore, the present experiment was more sensitive than those conducted previously.

During lactation, our LP sows consumed less feed, and nursed numerically fewer piglets (intensive group: 9.6 vs. 10.2; all: 9.8 vs. 10.1). The number of piglets nursing, regardless of feed intake, influenced milk production because milk consumed per piglet per day was not affected by dietary treatment. It can be argued, however, that the reduction in feed intake of the sow may have been the direct result of the low protein diet, whether it was related to diet composition, or dietary amino acid or net energy concentrations. Because both feed intake and the number of piglets nursing influenced milk production, they were used as covariates to distinguish whether dietary treatment, or management and sow variation was the major determinant of milk production (Table 5.2.1). When these two factors were both included in the analysis, as covariates, milk production was not different between LP and HP sows, indicating that the dietary treatment, itself, did not cause the majority of the observed decrease in milk production.

A potential explanation of the observed lower milk production in LP sows, is that the smaller birth weight of piglets suckling LP sows likely resulted in lower suckling stimulus to the udder (King et al, 1997), causing slightly lower initial milk production, and possibly reducing feed intake. This lower feed intake of LP sows resulted in the occurrence of amino acid and energy deficiencies, and energy intake has been suggested to be the primary controller of milk production in the sow (Tokach et al, 1992a). Therefore, if energy intake were insufficient, milk production would be reduced. With lower milk yield, growth rate of piglets nursing LP sows would be lower, and piglets on LP sows would be lighter than piglets nursing HP sows, further exacerbating the difference in milk production between HP and LP sows. The

lower birth weight of piglets from LP sows was not likely related to dietary treatment during gestation, because this diet provided sufficient amino acids. More likely, it was a reflection of natural sow variation, and an unintended bias for LP sows to birth smaller piglets. While not included in the selection criteria for this study, first litter performance data, before selection for this study, was available for our sows; post-hoc examination of these data indicated that the sows selected for the LP diets birthed slightly smaller piglets than those selected for the HP diets (1.20 kg vs. 1.29 kg).

Milk yield of lactating sows is often used as an indicator of nutritional status during lactation. Since piglets depend primarily on milk for growth, it is important to understand how dietary manipulations influence milk production. Direct determination of milk yield is not possible with sows (Etienne et al, 1998), and must therefore be estimated. Piglet growth rate is an indicator of the sow's capacity to support her litter, both during gestation and lactation, and can be used to estimate milk production. However, accurate figures of conversion efficiency of milk yield to piglet gain are required, and much variation exists in the current estimates describing the relationship between milk yield and piglet growth (Etienne et al, 1998). Estimates of efficiency range from 3.1 g milk per g of piglet gain (Klaver et al, 1981) to 3.8 g/g (Noblet and Etienne, 1986) with an average of 3.7 g/g (Noblet and Etienne, 1989) when the weigh-suckle-weigh technique is used. Using the deuterium oxide dilution technique, Auldist et al (1998) calculated that piglets in their experiment required 4.88 g milk / g gain from day 14 to 28 of lactation. The observed differences in efficiency of use of milk for piglet growth may be due to the differences in the method used or to animal differences. The deuterium oxide dilution technique uses an isotopic tracer, injected into the piglet, to measure body water (Pettigrew et al, 1987). Blood samples are taken over a period of time to determine the dilution of the tracer in the body water pools. Assuming that piglets only have access to water as milk, the extent of dilution of the tracer in the body water can be used to determine milk consumption. Using deuterium oxide as a tracer should give reasonably accurate estimates of milk production

(Auldist et al, 1998), but must be repeated several times during lactation due to high rates of body water turnover. Furthermore, the deuterium oxide dilution technique requires that piglets undergo a four-hour equilibration period, which prevents them from nursing during this period, and thus may affect the subsequent estimate of milk consumption. Alternatively, the traditional method of determining milk yield is by weigh-suckle-weigh. The weigh-suckle-weigh method can underestimate yield (Speer and Cox, 1984) due to disruption of the sow and litter (Pettigrew et al, 1985). Measurements, however, can be acquired in a single day, without specialized equipment, and provide immediate results. Also, correction equations have been developed to account for metabolic water losses, urination and defecation of the piglets to increase the accuracy of the procedure (Klaver et al, 1981; den Hartog et al, 1983; van Kempen et al, 1985; Noblet and Etienne, 1986; Sinclair et al, 1999).

Pettigrew et al (1985) compared isotope dilution and weigh-suckle-weigh on the same day. These authors measured milk yield using isotope dilution on days one and three of the test period, and measured yield using both techniques simultaneously on day two, and found that the two measurements gave similar intake estimates, for that day. However, the milk yield estimate for day two, with the weigh-suckle-weigh measurement, was lower by 11.9%, compared with the milk yield estimate for the average of the day previous and subsequent to that measurement, estimated from isotope dilution only. This author concluded that the social disruption of the sow and her litter, caused by weigh-suckle-weigh, reduced milk production of the sow.

Our observations of milk yield and piglet performance support the hypothesis that sows fed low protein, amino acid supplemented diets will exhibit similar performance to those consuming a conventional, intact protein diet.

If milk yield is underestimated by 11.9% using the weigh-suckle-weigh technique (Pettigrew, 1985), then the average milk yield during the present experiment was likely closer to 8.3 kg per day during parity two, and 10.0 kg per day during parity three. The adjusted yield for the second parity was lower than estimated by the NRC (1998) model (9.2 kg), whereas third

parity adjusted yield was higher than that given by NRC model (9.4 kg). Because the NRC (1998) was not able to accurately predict the milk yield of these sows, it is also probable that the estimate of amino acid requirements was not reflective of the actual requirements of our sows.

As lactation progresses, milk production increases, reaching a maximal level by approximately the third week of lactation (Klaver et al, 1981; Noblet and Etienne, 1986). Therefore the observed increase in milk yield from day 7.5 to day 16 of lactation was expected. Very few studies have experimentally validated the assumption that milk yield increases with increasing parity (Etienne et al, 1998); however, because third parity sows are more mature, with a greater mammary capacity, larger body size, and greater feed intake, their milk production was expected to be greater than second parity sows. In our study, third parity sows did, indeed, exhibit milk production greater than their own second parity yields (Table 5.2.1). In addition, based on trends toward interactions between stage and parity on milk yield, it was apparent that third parity sows had a greater capacity than second patity sows to increase milk production as lactation progressed (Table 5.2.2). In agreement with the increase in milk production from second to third parity, piglets from third parity sows were smaller at birth than those from sows in their second parity; however, piglet weights at weaning were similar for the two parities (Table 5.1.5), indicating increased milk production during parity three. Additionally, nursed piglets from parity three sows tended to be smaller initially, but were larger at weaning than nursed piglets in parity two, also indicating that sows increased their milk production from parity two to parity three. During the third parity, both feed intake and milk production of sows was greater, while weight loss was smaller, indicating that sows were experiencing lower nutrient deficit during parity three, compared to parity two.

Simple correlation of sow related factors on milk yield indicated that lactation nutrient and feed intakes were reasonably well correlated with milk yield ($r = 0.40$, $p \leq 0.0002$), as were the number of piglets nursing, average piglet weight and day of lactation ($r = 0.37$ to 0.41, $p \leq 0.0005$). From the analysed regression of sow factors (Table 5.2.4), 24-hour feed intake,

beginning the afternoon before weigh-suckle-weigh was the primary factor influencing milk yield, suggesting that milk production is very sensitive to short-term alterations in daily feed intake. Additionally, this agrees with the results of the covariate analysis of milk yield, where including feed intake as a covariate, negated differences in milk yield between the dietary treatments. Weight loss of the sow was also an important determinant of milk yield. As weight loss increased, milk yield decreased, indicating that the sow may reduce milk output to reduce tissue mobilization, and prevent further weight loss. Furthermore, the degree of weight lost during lactation is related to the nutrient intake of the sow (Boyd et al, 2000). Clowes (2001), suggested that a critical loss of 10 to 12% of initial body protein mass is required, and that only when the mobilization of endogenous (body) protein cannot compensate for the dietary protein deficit, will milk production decrease. However, our study indicates that the correlation between weight loss and milk yield was present, and significant, even with reasonably low levels of maternal tissue loss (i.e. 11 kg). The positive relationship between sow body weight at farrowing and milk production was likely related to the age and parity of the sow. Larger sows have greater body stores to support milk synthesis, and generally will enter lactation at an older age than smaller sows. Generally, a linear relationship between milk yield and number of piglets nursing has been observed (King et al, 1989). In our regression, the number of piglets nursing was positively correlated with milk yield, most likely through increased suckling stimulus provided by larger litters. Similarly, piglet weight was positively correlated with yield, because larger piglets are capable of more fully extracting milk from the teats, additionally increasing sucking stimulus (King et al, 1997). It was notable that the weight of the piglets, rather than day of lactation was selected in the prediction of milk yield. In support of this, one study found that milk production increased by 26% in the first week, when two-week old piglets were allowed to suckle newly farrowed sows, whereas milk production was reduced by 22% when newborn piglets were fostered to sows in their third week of lactation (King et al, 1997).

6.1.4.2 Milk Composition

Our observation that feeding sows a low protein diet in gestation and lactation reduced the concentrations of nutrients in milk (Table 5.2.5) disagrees with the available literature (Mennenga, 1986; Falaschini et al, 1994; Renaudeau and Noblet, 2001). Generally, no reduction in milk protein has been observed, although several studies in which adequate amino acid supplementation was not provided have noted reductions in milk crude protein content (King et al, 1993b; Al-Matubsi et al, 1998; Sinclair et al, 1999; 2001). Dietary treatment has been shown to influence milk fat and energy. Several studies have observed that increasing the fat content of the diet can increase the concentration of fat in the milk (Babinszky, 1998; Tilton et al, 1999). This may have relevance for our study, because the fat content of the low protein diets was approximately 50% of the fat content of the HP diets, for both gestation and lactation (Table 4.1.1; Table 4.1.3). Alternatively, the reduction in milk crude protein may have been a reflection of the reduced protein and amino acid supply given to the LP sows. Calculations of amino acid intake, against predicted requirement (Table 5.3.7), indicated that intensive LP sows were consuming inadequate lysine, valine, methionine, isoleucine, and threonine. This reduction in amino acid intake may have altered the metabolism of the sow, and thus reduced milk protein concentration. However, the plasma amino acid data, discussed earlier, indicated that deficiencies in amino acid intake, except lysine, either did not occur, or were not severe. As well, the crude protein content of milk from sows fed the low protein diet was similar to literature milk protein values (Klobasa et al, 1987; Darragh and Moughan, 1998; Sinclair et al, 1999).

The composition of milk has been shown to change as lactation progresses (Klobasa et al, 1987; Sauber et al, 1998; Jones and Stahly, 1999). Klobasa et al (1987) observed a slow decline in milk protein concentration from day two, to three weeks post farrowing, while total solids and fat content remained relatively stable during this period. This agrees with our

findings, where milk protein decreased from early to late lactation, and dry matter, fat and gross energy contents did not change significantly (Table 5.2.5). Other studies have observed decreases in the concentrations of milk dry matter, fat, energy and protein as lactation progressed (Sauber et al, 1998; Jones and Stahly, 1999), however, both these studies manipulated dietary protein and amino acid supplies. The decrease in milk protein concentration over the course of lactation could reflect a change in the relative contribution of whey and casein proteins to the total protein content (Klobasa et al, 1987; Gallagher et al, 1997). This observation, however, also suggests that the capacity of the gland to synthesize protein is limited by the metabolic activity of the mammary cells (Boyd and Kensinger, 1998). That we do not see decreases in milk fat concentration between days 7.5 and 16 of lactation is likely a function of the direct transfer of lipids from the blood to milk, whereas protein found in the milk must be synthesized in the mammary gland. The lack of parity differences in milk composition is in conjunction with Klobasa et al (1987), suggesting that synthesis and inclusion of milk constituents is independent of the maturity of the sow.

Simple correlation statistics revealed very little correlation between milk protein concentrations and sow related factors (Table 5.2.3), however, the multiple regression of sow factors on milk protein concentration indicated a complex relationship between factors influencing the sow, and milk production (Table 5.2.6). The decrease in milk protein concentration with increasing day of lactation has been observed in several studies (Klobasa et al, 1987; Sauber et al, 1998; Jones and Stahly, 1999), and was likely related to increasing milk production as lactation progressed (and piglets grew larger). Similarly, increased litter size correlated to greater lactation yields, and is probably due to greater metabolic demands on the gland for milk protein synthesis. The negative relationship between sow weight loss and milk protein concentration and output indicates that the sow will reduce milk protein synthesis, and thus protein output, in the mammary gland to prevent further maternal tissue mobilization.

Feed, protein and lysine intake negatively influenced milk protein concentration, while digestible energy intake positively influenced milk protein concentration. The fact that nutrient intake, independent of feed intake, influenced milk crude protein concentration, suggests that one or more nutrients, in addition to energy may have been limiting maximal milk protein; possibly lysine. If lysine supply from the diet and maternal tissue was inadequate to support increased milk protein synthesis, but energy supply was sufficient to maintain lactose synthesis, milk protein would be diluted (Jones and Stahly, 1999). However, the positive relationship between energy intake and milk protein concentration suggests that digestible energy intake was limiting the rate of milk protein synthesis in the mammary gland. Interestingly, the regression describing the relationship of sow factors on daily milk protein output, suggests that the negative relationships observed between milk protein concentration and feed intake variables (Table 5.2.6a) were probably due to confounding changes in daily milk volume and concentrations of milk nutrients.

A positive relationship between crude protein intake during lactation and milk dry matter was observed, such that increasing protein intake increased dry matter (Table 5.2.7). Combined with the results of the milk protein multiple regression (Table 5.2.6), this suggests that the increase in dry matter must be due to milk fat, because milk protein % was negatively related to increased dietary protein intake. It appeared that milk fat and energy were mainly influenced by energy supply from the maternal body (fat stores), and not energy supply from the diet, because backfat loss entered the multiple regression, and energy intake did not (Table 5.2.8; Table 5.2.9), whereas digestible energy intake was included in the multiple regression for milk protein. Contrary to our results, diets supplemented with fat in late gestation and in lactation have been shown to raise the fat content of the milk (Pettigrew et al, 1981). This is interesting to note, because the low protein diets contained less tallow, and contained approximately half as much crude fat as the HP diets, during both gestation and lactation. However, many of these studies examining the effects of supplemental dietary fat on milk fat

have been inconsistent in their ability to show a response. Additionally, few experiments have been comprehensive enough to examine the effects of multiple factors on milk composition.

In this study, the influence of backfat depth at farrowing and its loss during lactation implies that mobilization of body fat does not increase milk fat. This is probably because the fat mobilized from the body, in this study, was used for energy, and negative energy balance (as observed in our sows) would mean less fat was available for deposition in milk.

6.1.4.3 Milk Amino Acid Concentration

Very few studies have examined the effect of dietary protein supply on the amino acid composition of sow's milk. One study, that examined the effect of dietary protein on milk protein concentration, found that, while milk yield was reduced with decreased dietary protein, the concentration of protein in milk and the amino acid composition of milk protein were not affected (King et al, 1993a). The inability of diet to influence protein bound amino acids in milk indicates that the amino acid content of milk proteins is largely immutable. In our study, the majority of amino acids were not influenced by dietary treatment, however, glycine was increased in the milk protein from sows fed the low protein, amino acid supplemented diet. It is unclear why this amino acid was affected by dietary treatment, while all others were not, however, glycine is a small molecule, and easily synthesized from a variety of sources. Alternately, glycine is a major component of connective tissue (Kim et al, 1999) and it's increased presence in the milk (Table 5.2.10) and plasma (Table 5.5.3) of sows fed the low protein diet may suggest increased catabolism of connective tissue in the mammary gland or elsewhere in the body.

The amino acid content of milk protein appeared to be lower than literature values for several amino acids, but not for others (van der Peet-Schwering, 1998). This may have been due to differences in analytical method, or in true differences in amino acid content. There is considerable variation in the literature values, indicating that animal factors may influence the

amino acid content of milk. For example, the average lysine content of milk protein has been calculated as 7.48 g/ 16 g N, with a range from 7.09 to 7.86 g lysine/16 g N (van der Peet-Schwering et al, 1998). Other than lysine, all the indispensable amino acids analysed were lower than, or on the lower end of these concentrations. The lower amino acid contents generated in our study may have resulted from degradation of amino acids during acid hydrolysis, however, we used a procedure similar to that of King et al (1993a). Although total amino acid content of milk protein appeared low, a portion of this was due to methionine, cystine, proline and tryptophan not being analysed with our procedure. These four amino acids would account for approximately 17 grams amino acids per 16 g of nitrogen.

6.2 Effect of Low Protein, Amino Acid Supplemented Diets on Sow Metabolism

The ability of low protein, amino acid supplemented diets to reduce urinary nitrogen excretion has been well documented in growing-finishing pigs (Kerr and Easter, 1995; Sutton et al, 1999; Lee et al, 2001), and to a lesser extent, in lactating sows (Renaudeau et al, 2001). However, there is also an energy cost associated with the catabolism of amino acids and excretion of the excess nitrogen (Just, 1984), and if the amount of amino acid catabolism is reduced, the amount of energy required for this process is also decreased. Therefore, more of the consumed energy is available for tissue deposition, increasing the metabolic efficiency of the animal. Reductions in heat production with low protein diets have been documented for growing pigs (Le Bellego et al, 2001); however, verification of this relationship has not previously been undertaken in producing sows.

6.2.1 Nitrogen Excretion

Adequate dietary nitrogen (as amino acids) is required to support body processes, however, excess amino acids are catabolized and their nitrogen excreted in the urine (Lenis, 1989). The most recognized method to measure the adequacy of dietary nitrogen supply is

nitrogen balance. Balance studies allow for the calculation of nitrogen retention when intake and excretion of nitrogen by the animal are measured (Quinou et al, 1995). Such studies can be repeated several times per animal. However, they are laborious and time consuming (Maynard and Loosli, 1969), and require proper equipment to allow for the complete collection of feces and urine, which sows excrete in considerable quantities. Furthermore, with lactating sows, nitrogen excretion in milk cannot be quantitatively determined (Etienne et al, 1998), and must therefore be estimated. Because adequate facilities for total collection were unavailable, an alternate method of determining nitrogen excretion was required.

As stated in the review of the literature, nitrogen excretion in fecal material is not significantly influenced by dietary protein (Kerr and Easter, 1995), whereas urinary nitrogen excretion is. Therefore, for the purposes of this experiment, measurement of relative differences in the excretion of nitrogen in the urine was considered sufficient to evaluate dietary differences. The amount of urea excreted in the urine is related to the protein content of the diet (Folin, 1905, in Zlatnik, 1979) and will change with changes in protein intake, whereas the amount of creatinine excreted in the urine is reasonably independent of dietary protein levels, but is an index of muscle mass, in a fairly constant relationship (Kertz et al, 1970; Simmons, 1972; Duggal and Eggum, 1978). The urinary urea nitrogen to creatinine ratio can thus represent relative changes in nitrogen excretion due to changes in dietary protein intake. The accuracy of this method to estimate recent protein intake has been validated in humans (Zlatnik, 1979; 1981) and cattle (Kertz et al, 1970) and has been utilized to determine valine requirements in growing pigs (Lewis and Nishimura, 1995). Furthermore, several studies have documented the high correlation between results obtained from 24-hour urine collections and untimed samples (Zlatnik, 1979 r=0.798; 1981 r = 0.862; Swaminathan et al, 1979 r = 0.914), allowing single spot samples of urine to be effectively utilized for the determination of relative nitrogen excretion.

With an average decrease in dietary crude protein content of 2.8%, we observed an overall decrease in relative nitrogen excretion of 26% for sows fed the low protein diets (Table 5.5.1). This agrees closely with the general consensus that, for each 1% reduction in crude protein content of the diet, urinary nitrogen excretion is reduced, on average, by 8% (Jongbloed and Lenis, 1992; Kerr et al, 1995; Sutton et al, 1999; Lee et al, 2001), and supports the hypothesis that urinary nitrogen excretion is reduced in sows fed low protein, amino acid supplemented diets. While nitrogen and creatinine excretion in the urine samples were not affected by dietary treatment (Table 5.5.1), the ratio of nitrogen to creatinine illustrated that sows fed the low protein diets had considerably less urinary nitrogen excretion, indicative of the decrease in nitrogen intake by these animals.

To the authors knowledge, comparisons in urinary nitrogen excretion of sows between gestation and lactation, during different stages of these physiological states, or between parities have not been previously reported. Relative urinary nitrogen excretion was lower during gestation (Table 5.5.1), indicating lower nitrogen intake, and possibly consumption of less excess amino acids, although calculated amino acid intake indicated that gestating sows were still consuming amino acids above their requirements (Table 5.3.1; Table 5.3.2). The increase in relative nitrogen excretion from gestation to lactation was likely due to the increased intake of nitrogen (crude protein) during lactation (Table 5.1.6). Alternatively, amino acid intake calculations for lactation indicated that at least one amino acid was consumed below requirement (Table 5.3.4; Table 5.3.5), resulting in the mobilization of maternal tissue during lactation, to support milk synthesis. This catabolism of maternal tissue would have increased the circulating concentrations of several amino acids in the plasma, above their gestation concentrations, and increased the excretion of nitrogen, due to the additional tissue derived nitrogen. In agreement with this, we observed increased concentrations of several amino acids associated with muscle tissue catabolism (Table 5.5.3). However, urinary creatinine excretion

did not increase during lactation, suggesting that muscle tissue was not extensively catabolized during lactation.

The increase in relative nitrogen excretion from second to third parity reflected the increase in feed, and thus, amino acid intake during the third parity. With respect to their requirement, third parity sows consumed a greater excess of amino acids than second parity sows, during both gestation and lactation (Tables 5.3.1, 5.3.2; Tables 5.3.4, 5.3.5).

The significant interaction among physiological state, stage and parity enabled us to examine the pattern of nitrogen excretion during the entire experiment (Table 5.5.2). Relative nitrogen excretion was lowest in late gestation of the second parity, indicating that these sows were consuming the lowest excess of amino acids at this point. While the reduction in nitrogen excretion from early to late gestation only tended to be significant, this decrease also suggested that second parity gestating sows have a higher amino acid requirement during late gestation than in early gestation. This drop did not occur during gestation of their third parity, and notably all relative nitrogen excretion values were higher during parity three (Table 5.5.2) (except late lactation, which was not significant, but numerically higher). Gestating sows consumed all amino acids in excess of their requirements (Table 5.3.1), therefore, the decrease in relative nitrogen excretion in second parity late gestation was likely not an indicator of amino acid deficiency, but more likely an indicator that sows were consuming amino acids closer to their actual requirement at that time.

Nitrogen excretion was lower for all time points during the second parity, likely a reflection of the lower intake of amino acids, relative to the requirement, compared to the third parity (Tables 5.3.1 and 5.3.2; Tables 5.3.4 and 5.3.5). Interestingly, despite the increase in feed intake from early to late lactation, relative nitrogen excretion did not increase. This indicates that intake increased in response to increasing amino acid requirement, thus the extra nitrogen consumed was efficiently utilized for metabolic purposes (milk production, body weight recovery).

Addition of dietary effects to the three-factor interaction enabled us to observe differences in the pattern of nitrogen excretion between the diets. Relative nitrogen excretion of LP sows followed a similar pattern during the second and third parity, while the pattern for HP sows, changed from the second to third parity. This difference in response suggests that sows fed the low protein diets in gestation and lactation consumed a better balance of amino acids throughout their production cycle. HP sows were probably overfed protein during late gestation and early lactation of their third parity, because their relative nitrogen excretion increased during these periods (Figure 5.5.2). Alternatively, these sows may have been underfed during this period in parity two, although amino acid intakes, and plasma concentrations of amino acids do not suggest this. It is possible that LP sows were underfed protein throughout their second parity, however this seems unlikely during gestation, as sows exhibited considerable weight gains during this period. More likely, sows consumed greater excesses of amino acids, relative to their requirements during their third parity, but consumed sufficient amino acids to meet their requirements during both parities. Interestingly, second parity HP sows exhibited a dramatic rise in relative nitrogen excretion from early to late lactation, suggesting that the amino acid supply in the diet did not match the amino acids required for milk protein synthesis very well, at that large excesses of amino acids were consumed at this time. This rise was not observed in parity three, suggestive of a better match of supply versus requirement in this parity.

The increase in relative nitrogen excretion in LP sows during early lactation of the second parity, compared to nitrogen excretion in gestation, is in agreement with the overall nitrogen excretion results. These data suggest that sows consumed adequate amino acids, because the increase in nitrogen excretion would indicate greater consumption of excess amino acids. Alternatively, the observed increase might have been due to increased tissue protein catabolism to supply amino acids to milk synthesis, indicating that sows were deficient at this time. Since we also observed an (non-significant) increase in nitrogen excretion during parity

three, with sows exhibiting lower weight loss than the second parity, intake of amino acids was probably adequate in both parities.

The environmental impact of lower nitrogen excretion must also be considered. Based on the data of Dourmad and Etienne (2002), gestating sows fed 2.75 kg of a conventional 14.3% CP diet will consume approximately 61.9 g nitrogen, and will excrete 40.1 g urinary nitrogen. Therefore, the 25% reduction in urinary nitrogen excretion observed in this experiment, due to amino acid supplementation, would result in sows excreting 30.1 g N per day. This would reduce excretion of nitrogen by 1150 grams, over the course of a 115-day gestation. Assuming that lactating sows, given ad libitum access to a conventional 18.6% CP diet, consume 5.37 kg of feed (172.5 g N) and excrete 79.1 g urinary nitrogen per day (Clowes, 2001), the 26% reduction in urinary nitrogen excretion would result in sows excreting only 58.5 g N/day. This would amount to a reduction of 432.6 g of urinary nitrogen during a 21-day lactation. Therefore, use of low protein diets during both gestation and lactation would potentially reduce urinary nitrogen excretion, over the course of one reproductive cycle by approximately 1.6 kg per sow. Extending this to a typical herd of 1000 sows achieving 2.3 reproductive cycles per year results in a reduction of 3680 kg of nitrogen per year.

6.2.2 Energy Expenditure

Heat production can be measured directly by physical methods or indirectly, through measurements of gas exchange in respiration chambers, or through calculations of nitrogen and carbon balance (McLean and Tobin, 1987). Balance studies measure the amount of carbon and nitrogen ingested, excreted, and retained in the animal. To accurately determine heat production, gaseous excretion of carbon (as CO_2 and CH_4) must also be measured. Direct calorimetry measures the rate of heat dissipation as determined by changes in temperature and humidity whereas indirect calorimetry measures the rate of heat generation calculated by gas consumption and production. Alternatively, indirect calorimetry can be performed using

closed-circuit (air tight) or open-circuit (constant air flow) systems. The open-circuit respiration system, equipped with monitors to measure oxygen and carbon dioxide concentrations in respired and ambient air, is the most common method of measuring gas exchange in large animal studies. As well, respiratory analysis of oxygen and carbon dioxide provides a reasonable estimate of heat production (McLean and Tobin, 1987), which can be calculated using the formula of Brouwer (1965):

$$M\ (kJ) = 16.18 * V_{O2} + 5.02 * V_{CO2} - 5.99 * N - 2.17 * V_{CH4},$$

where M is heat production, V is volume of gas in litres, and N is nitrogen excreted.

6.2.2.1 Overall Energy Expenditure

To the authors knowledge, energy expenditure of gestating and lactating sows fed low protein, amino acid supplemented diets, by indirect calorimetry, has not been previously reported. Additionally, very few studies have examined the effects of physiological state, stage of gestation or lactation, and parity on energy expenditure (Close et al, 1985; Noblet and Etienne, 1987), and none have examined these under low protein feeding regimens. The lack of interactions between diet and the other main effects tested, indicated that overall energy expenditure of sows from both dietary treatments responded similarly to changes in physiological state, stage and parity. With reduced intake of excess amino acids, less of the digestible energy is utilized to catabolize those amino acids, increasing the amount of energy available for tissue deposition (Le Bellego et al, 2001) and other metabolic processes. Since we observed a decrease in nitrogen excretion, and there is an energy cost associated with nitrogen catabolism and excretion, we would also expect to find a reduction in heat production. Sows fed the low protein diet demonstrated an overall reduction in carbon dioxide excretion of 6.6% and reduction in daily heat production of 8% (Table 5.6.1), indicating that these sows utilized the available energy more efficiently, over the course of the experiment. As well, heat produced per unit of metabolic weight was lower, further supporting the hypothesis that sows fed low

protein, amino acid supplemented diets will be more energetically efficient, and will utilize dietary energy to a greater extent. The overall respiratory quotient (RQ) was similar between HP and LP sows (Table 5.6.1), indicating that sows utilized similar proportions of substrates during the study. The increase in gas exchange and heat production from gestation to lactation was expected, because lactating sows have both greater feed intake and increased metabolism, compared to gestating sows. The increase in RQ from gestation to lactation was likely an indicator of differences in diet composition, and feed intake, and suggests that lactating sows utilized more of the carbohydrates in the diet for metabolic processes. Additionally, the increase in gas exchange and heat production with increasing parity was likely due to increased feed intake, and body weight of the sow, and an increase in metabolism caused by larger litter sizes and milk production. When heat production was calculated on a metabolic body weight basis, heat production followed an opposite trend, with lower heat produced per unit of metabolic weight in parity three, compared to parity two. Because sows were larger in their third parity, maintenance heat loss accounted for a larger proportion of their heat production. Furthermore, changes in metabolic body weight are not linear with changes in total body weight, therefore, the large weight gain observed from parity two to parity three would only equate to a small change in metabolic body weight. Therefore, despite the greater mass of the sows during parity three, they had lower heat production per unit of metabolic weight, than during parity two. Interestingly, the respiratory quotient increased from parity two to parity three (Table 5.6.1). The lower RQ during parity two indicated that sows were utilizing more fat during this period, than in the third parity, which concurs with the greater fat loss of lactating sows during the second parity, and the loss of backfat observed during late gestation of that parity (Table 5.1.2).

There was a significant interaction between physiological state and parity for gas exchange and heat production (Table 5.6.2), such that CO_2 production increased during gestation and lactation with increasing parity, while O_2 consumption and heat production

remained similar across parities during gestation, and increased from parity two to parity three during lactation. The increase of all three measures during lactation reflected the increases in maternal body weight, feed intake and litter size in the third parity. Although gestating sows also increased body mass from their second to third parity, with a concomitant increase in feed and nutrient intake, only CO_2 production increased. This suggests that gestating sows required less oxygen to utilize the available nutrients, and thus produced less heat. Because more oxygen is utilized during the oxidation of fat, compared to carbohydrates, the increase in RQ during gestation, from parity two to parity three (Table 5.6.4), indicates that second parity sows were utilizing fat to supply energy, while during the third parity, more carbohydrates were utilized.

The change in heat production expressed on a metabolic weight basis with physiological state and stage indicated that overall metabolism of the sow was altered during the production cycle (Table 5.6.3). The decrease of heat production per unit of metabolic body weight from early to late gestation indicated that the sow utilized metabolizable energy more efficiently as gestation progressed. This is in opposition to the observations of Noblet and Etienne (1987), who calculated from energy balances that a 160 kg sow, gaining 0.65 kg per day, would exhibit an increase in heat production of 0.53 $kJ/kg^{0.75}$, for each day of pregnancy, as a result of increased maintenance energy requirements. However, it is highly unlikely that this magnitude of increase would be detectable by calorimetry equipment. During early gestation, the sows' own tissues are the main influence on metabolism, and maternal growth comprises a larger portion of weight gain. As gestation progresses, and especially from day 90 onward, growth of the fetus becomes considerable (Boyd et al, 2000). The reduction in heat produced per unit of metabolic weight from early to late gestation suggests that fetal tissue deposition utilizes available energy more efficiently than deposition of maternal tissue. A proportion of maternal tissue gain is fat, to replace that lost during lactation, whereas newborn piglets contain

very little adipose stores (Tilton et al, 1999); and the energy cost for fat deposition is considerably higher than that for lean tissue deposition (NRC, 1998).

6.2.2.2 Gestation Energy Expenditure

Calorimetry measurements were separated into gestation and lactation to account for differences in feed intake, and enable us to measure piglet influences on respiration.

Gestating sows fed the low protein, amino acid supplemented diet were more energy efficient than their conventionally fed counterparts, as indicated by their reduced gas exchanges and daily heat production (Table 5.6.4). As well, heat production per unit of metabolic weight of sows fed the LP diet was reduced. Increasing CO_2 production with increasing stage of gestation was likely due to the increase in body weight, and greater influence of fetal and mammary tissues on metabolism, from the beginning of gestation to late gestation. Fetal growth is extremely rapid during the final trimester (Noblet et al, 1997; Boyd et al, 2000), and these tissues are highly metabolically active. Additionally, mammary protein deposition increases three fold during late gestation (Boyd et al, 2000) and becomes increasingly metabolically active, in preparation for lactation (Noblet et al, 1997). Alternatively, the increase in CO_2 production, without increase in O_2 consumption may be reflective of the loss of backfat observed during late gestation of the second parity. Oxidation of body fat would increase carbon dioxide excretion, without increasing oxygen consumption, and would reduce the respiratory quotient. The lack of increase in heat production, with increasing stage of gestation is in opposition to Close et al, (1985) and Noblet and Etienne (1987), who both observed increased heat production as gestation progressed, using direct and indirect calorimetry, respectively. In the study of Close et al (1985), sows exhibiting increased metabolism were in negative energy balance during late gestation, which would have increased heat production; however in the study of Noblet and Etienne (1987), sows were in positive energy balance. An increase in heat production with the advancement of pregnancy may be

caused by variations in metabolic body size, maintenance energy requirements and energy retention, under constant feed intake (Noblet and Etienne, 1987). It is possible that any combination of these factors would cancel out the effect of increasing day of gestation on heat production.

Similar to the effect of stage of gestation on gas exchange, the increase in CO_2 excretion, but not in oxygen consumption or heat production during gestation, with increasing parity (Table 5.6.4) may reflect the mobilization of body fat during parity two, but not parity three. This agrees with the RQ data, which indicated that second parity sows utilized more fat, and third parity sows, more carbohydrates as their main energy source. Alternatively, increased carbon dioxide excretion is also a reflection of increased body weight, and fetal demand, due to greater number of piglets birthed in parity three.

The observed interaction between diet and parity on carbon dioxide production during gestation (Table 5.6.5) further supports the nitrogen excretion and amino acid intake results, which indicated that second parity sows had a higher requirement for amino acids than third parity sows. Because feed intake was altered to match body weight changes, it was used as a covariate for statistical analysis of energy expenditure measurements. Therefore, parity differences in carbon dioxide excretion were due to differences in dietary treatment and metabolic function, and not simply feed intake. Gestating sows from the two dietary treatments produced similar amounts of CO_2 during their second parity, which was lower than their carbon dioxide excretion in parity three. The increase in carbon dioxide production with increasing parity was more pronounced in HP sows, resulting in sows fed the HP diet producing more CO_2 than LP sows during their third parity gestation. The similarity in carbon dioxide production for the two dietary treatments during the second parity suggested that a limitation of energy and / or amino acids might have occurred during this period, to negate the positive effects of protein reduction on CO_2 production. That sows fed the LP diet exhibited a smaller increase in carbon dioxide production, compared to HP sows, from parity two to parity three suggested that LP

sows altered their metabolism during their third parity gestation. Alternatively, sows fed the low protein, amino acid supplemented diet entered their third parity gestation at a lower weight that HP sows, but proceeded to regain weight faster than HP sows, such that body weight was similar by the early gestation calorimetry measurement (Table 5.1.4; 5.1.7). Because backfat depth was similar between the two dietary treatments at all times, we can assume that the increased gain was largely protein. The energy cost associated with muscle protein deposition is less than that associated with fat deposition, and this may have been reflected in the lower carbon dioxide production and increased efficiency of LP sows during parity three.

6.2.2.3 Lactation Energy Expenditure

We observed a reduction in oxygen consumption and heat production in lactating sows fed LP diets, compared to sows fed the conventional diet (Table 5.6.6), which supports the hypothesis that feeding low protein, amino acid supplemented diets will result in sows that are more energy efficient. Sows fed the low protein diet excreted nearly 4% less carbon dioxide and almost 5% less heat on a metabolic body weight basis. The larger body weight loss of LP sows during lactation, compared to HP sows, with similar backfat loss, was a result of increased lean tissue mobilization and catabolism, which would be expected to increase CO_2 and heat production of sows fed the low protein diet, abolishing the possible benefits of reduced excess amino acid supply. In addition, sows were measured alone for only forty minutes, and activity level was greatly different (standing vs. laying) between animals, resulting in a larger standard error.

The absence of differences in gas exchange and heat production between early and late lactation (Table 5.6.6) indicated that the metabolism of the sow was high early in lactation, and was maintained, although milk production increased as lactation progressed. As well, similarity of the RQ between early and late lactation indicated that the proportion of substrates used for energy was also similar. The increase in carbon dioxide production with increasing parity was

likely related to the increases in body mass of the sows and number of piglets nursing the sow from parity two to parity three. Larger litters cause the sow to produce more milk, which increases the metabolic demands on the sow (Auldist et al, 1998), and thus heat production. Similar to the gestation measurements, we observed greater losses of body weight and backfat during lactation of the second parity, which may explain the lack of difference in oxygen consumption between the two parities. As in gestation, the greater fat mobilization in the second parity lactation would increase O_2 consumption, negating the differences in oxygen consumption caused by lower body weight during parity two. This increased mobilization of fat was also reflected in the lower respiratory quotient observed during the second parity (Table 5.6.6).

Because piglets were removed from the sow for a portion of the respiration measurement, we were able to obtain separate gas exchange and heat production data for the sow alone, and sow with her litter. The increase in gas exchange and daily heat production between the sow alone, and sow with her litter, can be assumed to be the result of piglet respiration. The effect of dietary treatment on gas exchange and heat production were the same for the sow alone, and sow with litter (adjusted for feed intake) (Tables 5.6.6; 5.6.7) indicating that the decrease in oxygen consumption and heat production observed was a result of the dietary treatment influencing the metabolism of the sow, and not the litter. As expected, gas exchange of the sow and litter and daily heat produced per piglet increased as lactation progressed (Table 5.6.7), mainly due to the large increase in piglet body weight during lactation. Heat production of the piglet, expressed relative to metabolic body weight, did not change with increasing age (day of lactation). The increase in carbon dioxide production with increasing parity was likely a result of both increased body weight of the sow, and increased milk production. That we observed a trend towards increased heat production from the piglet, and increased heat production per unit of metabolic body weight of the piglet may have been an

indicator of differences in piglet body composition between the parities, which could have resulted from the differences in milk yield (Table 5.2.1) and nutrient output.

As with nitrogen excretion, the environmental impact of reduced carbon dioxide excretion must be considered. In this study, gestating sows fed a conventional diet excreted 3024.2 grams carbon dioxide per day, in comparison with 2861.2 grams CO_2 per day excreted by sows fed the low protein diet. Over a 115-day gestation, this would result in a reduction in CO_2 excretion of 18.7 kg. Lactating sows fed the conventional diet excreted 4535 g CO2/day, whereas sows fed the low protein diet excreted 4359.6 g carbon dioxide, daily. This would amount to a reduction of 3.7 kg during a 21-day lactation. Therefore, use of low protein diets during both gestation and lactation would potentially reduce carbon dioxide excretion, over the course of one reproductive cycle by approximately 22.4 kg per sow. Extending this to a typical herd of 1000 sows achieving 2.3 reproductive cycles per year results in a reduction of 51 tonnes of carbon dioxide per year.

6.3 Economic Analysis

Low protein, amino acid supplement diets can be formulated, using least-cost diet formulation, to be comparable in price to conventional, intact protein diets (Table 5.7.1). The difference in price between conventional diets and low protein, amino acid supplemented diets, will depend on the prices of soybean meal and cereal grains, and the cost of synthetic amino acids. When the cost of soybean meal increases above a certain threshold value, it will be less expensive to utilize synthetic amino acids, and thus low protein diets. In this study, substitution of soybean meal with crystalline amino acids did not affect the cost of feeding one sow for one production cycle. However, piglets from HP sows brought in greater revenues per sow, due to greater numbers of piglets weaned from HP sows, and higher piglet weaning weights. The difference in number of piglets weaned was primarily due to (non significant) differences in fostering, and death rate, and not number of piglets born between the two groups, which was

similar between the dietary treatments in both parities. The reduced weaning weights observed with piglets nursing LP sows, however, indicated that growth rate of these piglets was compromised. This was supported by the milk production results, although the degree of reduction in milk production due to dietary treatment and that due to differences in the number of nursing piglets is difficult to determine. Other studies evaluating decreasing dietary crude protein to a similar, or greater extent than our study, and supplementing with limiting amino acids have not demonstrated differences in number of piglets weaned, or piglet weaning weights (Falaschini et al, 1994; Renaudea and Noblet, 2001; Trombetta et al, 2001), suggesting that piglet revenue could potentially be similar to revenue generated from piglets nursing sows fed high protein diets, and that margin over feed intake of LP diets could be similar to, or better than with conventional, intact protein diets.

Additionally, the cost benefits of reduced nitrogen and carbon dioxide excretion must be considered when utilizing low protein, amino acid supplemented diets. In the future, producers may be able to profit from the reduction in greenhouse gas emissions of their pigs, through the sale of carbon credits. Currently, carbon credits are valued at $15 to $60 per Tonne (Ball and Möhn, 2003). In our study, sows fed low protein diets exhibited a 32% reduction in greenhouse gas emission (26% reduction in N excretion, 6% reduction in CO_2 production). Through the reduced greenhouse gas emissions, considerable savings could be achieved by using low protein diets, over conventional diets.

7.0 SUMMARY AND CONCLUSIONS

7.1 Summary of Discussion

The low protein gestation diet was capable of supporting similar maternal weight and backfat gains as the conventional gestation diet. Gestation feed intake was similar across dietary treatments, however, LP sows consumed less digestible energy and crude protein than sows fed the HP diet. Although digestible energy intake was lower for sows fed the LP diet, LP sows gained a similar amount of backfat as HP sows, indicating that the net energy content of the two diets was similar. Gestating sows exhibited similar weight gains during parity two, however, sows fed the LP diet displayed larger weight gains during early gestation of the third parity, than HP sows; possibly an indication of compensatory gain, to refurbish the higher tissue loss that occurred during lactation. The lower piglet birth weights and milk production of sows fed the LP diet, as well as their lower feed intake, could have been a result of nutritional carry-over effects from gestation to lactation, however, this is unlikely, because the dietary supply of amino acids was higher than expected, and amino acid intake calculations suggested that dietary intake was sufficient, for both diets, during gestation. A combination of energy limitation and possible amino acid deficiency with the low protein diet during late gestation, of parity two, probably explains the decrease in feed intake and lower performance during the second parity lactation. However, it does not explain the differences in lactation performance observed in parity three. Concentrations of plasma amino acids did not indicate that any amino acids were deficient, as all were similar between diets during gestation, and it is more likely that amino acids were consumed in excess of requirement. However, it appeared that energy was limiting in the gestation diets during late gestation, at least during parity two, where we observed a decrease in backfat thickness. The reduction in amino acid consumption, without deficiency, resulted in a 23% reduction in urinary nitrogen excretion by sows fed the low protein diet, compared to the high protein diet, supporting the available literature. Additionally, the decrease

in excess amino acid intake allowed LP sows to utilize dietary energy more efficiently, as evidenced by their decrease in carbon dioxide production (5.4%), oxygen consumption (6.3%) and heat production (6%), compared to gestating HP sows.

Lactating sows receiving both dietary treatments consumed inadequate amino acids and energy to prevent body weight and backfat loss during the 21-day lactation. The lower feed and nutrient intake of sows fed the LP lactation diet led to a greater body weight loss, compared to sows fed the conventional, high protein diet. However, backfat loss was similar between the two dietary treatments, suggesting that LP sows mobilized more maternal protein tissue than HP sows. This is supported by the calculations of amino acid intake, which indicated that all sows consumed inadequate lysine, and that LP sows were more deficient in amino acids than HP sows. The inability of the low protein diet to support similar piglet growth rates does not agree with the observations from other studies examining low protein, amino acid supplemented diets. Most studies have noted that milk production was reduced only when dietary supply of amino acids, and energy was extremely low, and a high degree of maternal weight loss was occurring. In our study, however, weight loss was not excessive, with an average loss of 11 kg, by LP sows during the second parity, and only 5 kg during parity three. General consensus within the literature is that sows will reduce their milk production only when the loss of maternal tissue becomes too great, however, energy intake has been suggested to be the primary controller of milk production in the sow (Tokach et al, 1992a). Therefore, if energy intake were insufficient, milk production would be reduced. Since we observed similar maternal weight and backfat loss between the two groups during parity three, but lower milk production for LP sows, energy intake may have been inadequate to support milk production. An important consideration, however, is that no other studies have examined lactation performance when low protein diets were fed during both gestation and lactation, and we may have been observing dietary carry-over effects between gestation and lactation which have not previously been elucidated.

The evidence for deficiencies of amino acids, other than lysine, was not apparent in plasma amino acid concentrations. Plasma lysine was lower in lactating, compared to gestating sows, suggesting that this amino acid was consumed in inadequate quantities during lactation to meet the lysine requirements of our sows. The concentrations of other indispensable amino acids did not decrease below their gestation concentrations, and were within reference values from studies providing adequate amounts of amino acids in the diet. However, increased plasma concentrations of alanine, glutamine, proline, and hydroxyproline indicated that muscle protein mobilization was occurring, which is supported by the observed weight losses during lactation.

Although we observed higher weight loss for lactating sows fed the low protein diet, we observed that LP sows excreted 30% less nitrogen in their urine, compared to sows fed the high protein diet, indicating that, although consumption of lysine was inadequate, the balance of amino acids provided to these sows was better than the balance of amino acids in the high protein diet. Concomitant with the decrease in nitrogen excretion, heat production of lactating sows fed the low protein diet was 6.9% lower than heat production in HP sows, and oxygen consumption was 7.8% lower. Carbon dioxide production was reduced by 4%, compared to sows fed the high protein lactation diet, further indicating that sows fed the low protein diet utilized dietary nutrients more efficiently.

7.2 Conclusions

Because of the relative scarcity of information in the available literature, the overall objective of this study was to provide the scientific community, and swine industry, with a comprehensive picture of the productive and metabolic effects of feeding low protein, amino acid supplemented diets to gestating and lactating sows. In order to accomplish this, several hypotheses were proposed, regarding feeding low protein, amino acid supplemented diets. By examining a wide array of performance and metabolic characteristics, over the course of two

parities, we were able to evaluate effects of feeding low protein, amino acid supplemented diets to producing sows during different physiological states, specific timeframes within physiological states, and across parities, as well as determine dietary influences on performance and metabolism, in greater detail than previously examined.

Hypothesis #1 Properly formulated, low protein diets will support performance equal to that of sows fed a conventional intact protein diet.

In this study, gestating sows fed the low protein, amino acid supplemented diet gained similar body weight and backfat as sows fed the conventional diet. We also observed that third parity, gestating sows fed the LP diet gained more weight in early gestation than sows fed the high protein diet, possibly indicative of compensatory gain. Results of this study indicate that low protein, amino acid supplemented diets can be fed to gestating sows, promoting maternal gains similar to that of sows fed a conventional, intact protein diet.

Lactating sows fed the low protein diet consumed less feed, protein and digestible energy than sows fed the conventional diet. The cause of this reduction in feed intake is unknown, but may have been a result of differences in diet composition. Alternatively, consumption of net energy was probably similar between LP and HP sows, although digestible energy intake was less. The reduction in feed intake resulted in lactating sows fed the low protein, amino acid supplemented diet losing more body weight, but similar amounts of backfat, compared to sows fed the high protein diet. However weight and backfat loss, for both groups, was greater during their second parity lactation. Although sows fed the low protein, amino acid supplemented diet lost more weight during lactation, this did not influence their ability to rebreed after weaning, as evidenced by the similar wean-to-estrus intervals of sows the LP vs. HP diet, indicating that the amount of weight lost was not sufficient to cause reproductive difficulties. Indeed, an average weight loss of 8.8 kg in the second parity is considered minor.

Sows fed the low protein gestation diet birthed similar numbers of piglets, however these piglets were, on average, 60 grams lighter than those from HP sows. Piglets nursing LP sows were weaned lighter than those nursing HP sows, an observation that was supported by the reduced milk yield measured in lactating LP sows. Milk composition was altered by feeding the LP diet to gestating and lactating sows, such that dry matter, protein, fat and energy content of the milk was lower in the milk of LP sows, compared to milk from HP sows. The amino acid composition of milk protein, however, was not affected by dietary treatment. These results indicate that low protein diets for lactating sows can only be utilized when a firm understanding of animal potential, and amino acid and energy requirements is present. Additionally, it appears that modern sows may be highly sensitive to slight nutritional insults, and that younger sows will reduce milk production to preserve body tissues.

Hypothesis #2 Sows fed low protein diets with adequate amino acid supplementation will exhibit similar maternal gains (and losses) as sows fed conventional diets, and the composition of these weight changes will be similar.

As stated above, sow weight and backfat changes were similar between the two dietary treatments during gestation, suggesting that body composition was not affected by feeding the low protein diet. Interestingly, we observed that second parity sows lost backfat during late gestation, but did not lose backfat during their third parity gestation. Furthermore, backfat depth was not different between the two dietary treatments at any time during the study, indicating that energy supply to the sows was similar throughout the study. Body weight of sows fed the low protein, amino acid supplemented diet was lower at weaning, due to a greater loss of weight during lactation, especially during parity two. However, gestating third parity LP sows regained the weight lost during lactation faster than HP sows, so that all sows were similar weight by their early gestation energy measurements. The lower weights, but similar backfat depths of LP sows, at certain periods of the study indicated that these sows contained similar

fat, but less protein than HP sows. Unfortunately, due to difficulties with the analysis of plasma samples, deuterium oxide results are not included in this thesis. Thus, we cannot comment on exact body composition differences between the two dietary treatments.

Hypothesis #3 Feeding sows low protein, amino acid supplemented diets in one parity will not influence performance in the subsequent parity.

The lack of parity interactions for any of the performance characteristics measured indicated that sow response was similar from one parity to the next. If dietary treatment were to influence performance, we would expect to see interactions between parity and the other main effects. Additionally, the parity effects that were observed were generally those that were expected. However, the possible effect of low protein, amino acid supplemented diets fed during gestation on lactation feed intake, and piglet birth weight cannot be completely ignored. To the author's knowledge, this is the first study to examine feeding low protein, amino acid supplemented diets during both gestation and lactation, and one of few which has examined dietary effects in subsequent parities. The lack of pertinent information makes it difficult to speculate whether the gestation, or the lactation dietary treatment was the cause of the reduced feed intake of lactating LP sows. Additionally, one must question whether the difference in piglet birth weights was a result of dietary treatment, or the result of an unintended bias for LP sows to birth smaller piglets.

Hypothesis #4 Sows fed low protein diets with adequate amino acid supplementations will have lower urinary nitrogen excretion than sows fed conventional diets.

We observed an overall reduction in nitrogen excretion of 26%, with an average decrease in dietary crude protein of 2.8%, indicating that low protein, amino acid supplemented diets do reduce nitrogen excretion in the urine. This reduction agrees closely with other studies, which have generally utilized nitrogen balance to determine nitrogen excretion. Due to the

similarity of response, it is apparent that measuring the nitrogen: creatinine ratio in spot samples of urine is sufficient for determining relative urinary nitrogen excretion in adult swine. Furthermore, we examined the effects of physiological state, stage and parity on nitrogen excretion, and were able to elucidate differences between these effects. Particularly interesting, was the difference in excretion, and excretion pattern from parity two to parity three, indicating that the excess of amino acids provided in the diet was greater during the third parity.

Plasma concentrations of amino acids were influenced by a variety of factors, during gestation and lactation, such that dietary effects could often be explained by differences in metabolism and performance. The lack of differences in plasma amino acids during gestation suggests that both diets provided adequate amino acids to meet requirements. However, during lactation, plasma amino acid concentrations reflected the balance between amino acid intake, nitrogen excretion, contribution of amino acids from body tissue, and secretion of amino acids in milk. Based on the decrease in plasma concentration from gestation to lactation, it appeared that lysine was the first limiting amino acid in the lactation diets, and may have been fed below requirement during lactation.

Hypothesis #5 Sows fed low protein diets with adequate amino acid supplementations will have lower energy expenditure than sows fed conventional diets.

The overall 6.6% reduction in carbon dioxide excretion, and 8% reduction in heat production through the entire study, indicated that sows fed the low protein, amino acid supplemented diets were more energy efficient than sows fed the conventional diets. This could have profound effects, if utilized in environments where ambient temperature is detrimental to animal performance. Our data allowed us to examine gestation and lactation energy expenditure separately. During gestation, LP sows exhibited a 5.4% reduction in CO_2 production, and 6% decrease in heat production, also indicative of lower energy expenditure by these sows. Lactating LP sows did not exhibit significantly lower carbon dioxide production,

but did show reduced oxygen consumption, and 6.9% lower heat production. We speculated that a reduction in carbon dioxide excretion during lactation may have been masked by the short period of measurement for sows without their litter, leading to greater variance. Indeed, when sow and piglets were measured together, carbon dioxide production tended to be lower for sows fed the low protein diet.

Hypothesis #6 Low protein, amino acid supplemented diets will be economically competitive with conventional, intact protein diets for sows.

Low protein diets were successfully formulated, to be similar in cost to the traditional, intact protein diets, commonly used in Western Canada. However, due to the reduced performance of piglets (as a reflection of reduced milk production), revenue generated from sale of piglets nursing sows fed the low protein diets, was less than that from piglets nursing HP sows, leading to lower margin over feed cost for LP sows. It must be pointed out, however, that the majority of studies examining feeding low protein, amino acid supplemented diets to lactating sows have not observed reductions in piglet performance. Additionally, producers may soon be able to sell carbon credits, to take advantage of the reduction in greenhouse gas emissions achieved when using low protein, amino acid supplemented diets. Therefore, it is still highly likely that low protein diets can be economically competitive with typical intact protein diets.

8.0 FUTURE DIRECTIONS

The results of this study emphasize the need for further research in a variety of areas. Particularly noticeable, is the lack of long term data on the effects of feeding low protein, amino acid supplemented diets to sows. Due to the sow's ability to buffer nutritional insults, minor and even moderate deficiencies of amino acids or energy may not result in obvious or measurable alterations in performance for several reproductive cycles. Therefore, further experiments examining feeding such diets for several parities should be conducted.

Very few experiments (Mennenga, 1986; this thesis) have measured milk production by sows fed low protein, amino acid supplemented diets. Clearly, maintaining milk production of the sow is an important prerequisite for adequate piglet growth, and for the commercial acceptance of such diets. Therefore, further research to understand the mechanisms of amino acid and energy supply, and litter dynamics on milk production and the composition of milk is required.

Although unlikely, the presence of bloodmeal in our low protein lactation diet, may have induced the decrease in feed intake, possibly through reduced palatability. Furthermore, bloodmeal may not always be allowed in swine diets, and as such, further examinations of low protein wheat, barley, soybean meal diets, without bloodmeal, should be conducted. Because the order of limiting amino acids in diets based on wheat and barley is different than those based on corn, which is less commonly used in Western Canada, there is a deficit of information pertinent to these feedstuffs, for feeding low protein, amino acid supplemented diets. If such diets are to be used commercially, deficiencies of amino acids must be prevented, requiring greater awareness of the amino acid composition of commonly grown crops, and the nutrient requirements of animals consuming such feedstuffs.

It is unfortunate that plasma was only obtained during the second parity, when the D_2O study was conducted. It would have been interesting to observe whether the patterns in amino

acids were similar across the two parities, especially during lactation. Lactation of the second parity was characterized by higher weight loss, and lower milk production, compared to the third parity. However, feed and nutrient intakes were lower during the second parity. These data indicate that the profiles of amino acid in the plasma reflect the complex relationships of what is occurring metabolically within the lactating sow, and that these relationships, and their outcome in plasma deserve further scrutiny.

In this study, weight gains of gestating sows and milk production, and nursing capacity of lactating sows was higher than expected, leading to amino acid deficiency in both the high protein and low protein treatments, during lactation. This emphasizes the need for more, accurate, and current information on the performance of different genotypes of sows, and of sows in general. Information on the amino acid requirements for both gestating and lactating sows is surprisingly scarce, and use of the ideal amino acid concept for diet formulation should only be utilized when we are sure in our knowledge of the requirements. Therefore, further research on amino acid requirements, and re-examination of models currently used to describe metabolism in gestating and lactating sows is urgently required.

The growth performance potential of modern sows during gestation appears to have been underestimated by the feeding regimen adopted by the University of Alberta's Swine Research and Technology Centre. Since this regimen is similar to that used throughout the industry, it is important that it accurately estimate sow weight gains. In the present study we observed considerable growth rates of second and third parity sows, however second parity sows appeared to be receiving inadequate dietary energy to maintain backfat. This suggests that the energy requirements of modern young sows should be re-evaluated. Particularly interesting was the difference in response between second and third parity sows, suggesting that second parity animals should be considered separately from older, more mature sows; possibly similar to gilts. To that end, additional knowledge on the growth, productive capabilities and nutrient requirements of sows at different stages of maturity (parities) is needed.

In conjunction with the last two points, the inadequacy of the amino acid requirement tables provided in the NRC (1998) text must be emphasized. The text provides amino acid requirements for a limited number of animal weights and performance levels. Gestation weight gains were higher than described, and lactation starting weights were often much higher than the 175 kg sow suggested. With our modern, fast growing, large mature weight genotypes, the next NRC edition should account for high producing sows in their requirement tables.

Additionally, while the computer model provided in the NRC (1998) edition is an excellent tool for producers and researchers, alike, several unverified assumptions on metabolism, present in the sow model, make the current model inherently flawed. To better describe sow energy and amino acid metabolism and estimate requirements, these assumptions must be tested, and include: that the ideal protein pattern for maintenance and daily maintenance requirement for true ileal digestible lysine is the same as for growing pigs; that the ratio of amino acids required for milk production provided by NRC (1998) is the actual pattern; that the amino acid requirements for observed milk production also maximize subsequent reproductive performance; and that the digestibility of amino acids is similar for growing pigs and sows in a corn-soybean meal diet

9.0 LITERATURE CITED

AAFRD (Alberta Agriculture, Food, and Rural Development website; http://www.agric.gov.ab.ca/navigation/livestock/pigs/index.html

Agriculture Canada Bi-weekly Bulletin; http://www.agr.gc.ca/policy/winn/biweekly/e/ arche/archbbe.htm

Aherne, F., and G. Foxcroft. 2000. Management of the gilt and first parity sow: Part V. Nutritional management in gestation and lactation. VII Simposio Internacional de Reproducao e Inseminacao Artificial em Suinos. 131-144.

Al-Matubsi, H.Y., G. Bervanakis, S.M. Tritton, R.G. Campbell, and R.J. Fairclough. 1998. Influence of dietary protein of diets given in late gestation and during lactation on protein content and oestrogen concentrations in the colostrum and milk of gilts. Anim. Sci. 67:139-145.

AOAC. 1990. Official Methods of Analysis. 15th Ed. Association of Official Analytical Chemists. Washington, DC.

Auldist, D.E., L. Morrish, P. Eason, and R.H. King. 1998. The influence of litter size on milk production of sows. Anim. Sci. 67:333-337.

Babinszky, L. 1998. Dietary fat and milk production. In: The Lactating Sow. Chapter 8. . (Ed. M.W.A. Verstegen, P.J. Moughan, and J.W. Schrama). Wageningen University Press, The Netherlands. pp. 143-157.

Ball, R.O., and S. Möhn. 2003. Feeding strategies to reduce greenhouse gas emissions from pigs. In: Advances in Pork Production. Vol. 14. (Ed. R.O.Ball). Proceedings of the 2003 Banff Pork Seminar. pp 301-311.

Batterham, E.S. and R.D. Murison. 1981. Utilization of free lysine by growing pigs. Br. J. Nutr. 46:87-92.

Batterham, E.S., and H.S. Bayley. 1989. Effect of frequency of feeding of diets containing free or protein-bound lysine on the oxidation of [14C]lysine or [14C]phenylalanine by growing pigs. Br. J. Nutr. 62:647-655.

Bidlingmeyer, B.A., Cohen, S.A., and Tarvin, T.L. 1984. Rapid analysis of amino acids using precolumn derivatization. J. Chromatog. 336:93-104.

Boyd, R.D., and R.S. Kensinger. 1998. Metabolic precursors for milk synthesis. In: The Lactating Sow. Chapter 4. (Ed. M.W.A. Verstegen, P.J. Moughan, and J.W. Schrama). Wageningen University Press, The Netherlands. pp. 69-93.

Boyd, R.D., K.J. Touchette, G.C. Castro, M.E. Johnston, K.U. Lee, and In K. Han. 2000. Recent advances in amino acid and energy nutrition of prolific sows - review. J. Anim. Sci. 13: 1638-1652.

Brendemuhl, J.H., A.J. Lewis, and E.R. Peo, Jr. 1989. Influence of energy and protein intake during lactation on body composition of primiparous sows. J. Anim. Sci. 67:1478-1488.

Brouwer, E. 1965. Report of Sub-committee on Constants and factors. In Energy Metabolism. Proceedings of the 3rd Symposium. Ed. K.L. Blaxter. Academic Press, London.

Chen S.Y., J.P.F. D'Mello, the late W.H. Elsley, and A.G. Taylor. 1978. Effect of dietary lysine levels on performance, nitrogen metabolism and plasma amino acid concentrations of lactating sows. Anim. Prod. 27: 331-344.

Close, W.H., J. Noblet, and R.P. Heavens. 1985. Studies on the energy metabolism of the pregnant sow. 2. The partition and utilization of metabolizable energy intake in pregnant and non-pregnant animals. Br. J. Nutr. 53:267-279.

Clowes, E.J. 2001. Lactational protein loss and sow performance. Ph.D. Thesis. University of Alberta, Edmonton, AB.

Corley, J.R., M.W. Esch, J.M. Bahr, and R.A. Easter. 1983. Amino acid supplementation of low-protein diets for swine: effects of gestation treatment on reproductive performance of gilts and sows. J. Anim. Sci. 56:108-117.

Cuaron, J.A., R.P. Chapple, and R.A. Easter. 1984. Effect of lysine and threonine supplementation of sorghum gestation diets on nitrogen balance and plasma constituents in first-litter gilts. J. Anim. Sci. 58:631-637.

Darragh, A.J., and P.J. Moughan. 1998. The composition of colostrum and milk. In: The Lactating Sow. Chapter 1. (Ed. M.W.A. Verstegen, P.J. Moughan, and J.W. Schrama). Wageningen University Press, The Netherlands. pp.3–21.

Degussa Feed Additives. 1996. The amino acid composition of feedstuffs. 4th revised ed. Degussa AG, Hanau, Germany.

den Hartog, L.A., M.W.A. Verstegen, H.A.T.M Hermans, G.J. Noordeweir, and G.J.M. van Kempen. 1983. Some factors associated with determination of milk production in sows by weighing of piglets. J. Anim. Phys. Anim. Nutr. 51:148-157.

Duggal, S.K., and B.O. Eggum. 1978. Urinary creatinine and creatine excretion in pigs in relation to body weight and nitrogen balance. J. Sci. Food Agric. 29:683-688.

Eissen, J.J., E. Kanis, and B. Kemp. 2000. Sow factors affecting voluntary feed intake during lactation. Livestock Prod. Sci. 64: 147-165.

Etienne, M., J.Y. Dourmad, and J. Noblet. 1998. The influence of some sow and piglet characteristics and of environmental conditions on milk production. In: The Lactating Sow. Chapter 16. (Ed. M.W.A. Verstegen, P.J. Moughan, and J.W. Schrama). Wageningen University Press, The Netherlands. pp. 285-300.

Falaschini, A.F., L.A. Volpelli, and M.F. Trombetta. 1994. Effects of protein and/or amino-acid levels on reproductive performance and metabolic profile of lactating sows. Ann. Zootech. 43:151-161.

Fenton T.W. and M. Fenton. 1979. An improved procedure for the determination of chromic oxide in feed and feces. Can. J. Anim. Sci. 59: 631-633.

Fontaine, J., S. Bech-Andersen, U. Butikofer, and I. DeFroidmont-Gortz. 1998. Determination of tryptophan in feed by HPLC-development of an optimal hydrolysis and extraction procedure by the EU commission DG XII in three international collaborative studies. Agribiol. Res. 51:97-108.

Gallagher, D.P., P.F. Cotter, and D.M. Mulvihill. 1997. Porcine milk proteins: a review. Int. Dairy Journal. 7: 99-118.

Gatel, F., and F. Grosjean. 1992. Effect of protein content of the diet on nitrogen excretion by pigs. Livestock Prod. Sci. 31: 109-120.

Goering, H.K., and P.J. Van Soest. 1970. Forage fiber analyses. Agric. Handbook No. 379. ARS-USDA, Washington, DC.

Gomez, R.S., A.J. Lewis, P.S. Miller, and H.-Y. Chen. 2002. Growth performance, diet apparent digestibility, and plasma metabolite concentrations of barrows fed corn-soybean meal diets or low-protein, amino acid-supplemented diets at different feeding levels. J. Anim. Sci. 80:644-653.

Harper, A.E., R.H. Miller, and K.P. Block. 1984. Branched chain amino acid metabolism. Ann. Rev. Nutr. 4:409-454.

Heger. J., S. Mengesha, J. Blaha, and F. Koch. 1997. Estimation of minimum crude protein level in diets for high-lean growth pigs. Agribiol. Res. 50:64-77.

Johnston. L.J. M.Ellis, G.W. Libal, V.B. Mayrose, W.C. Weldon, and NRC-89 Committee on Swine Management. 1999. Effect of room temperature and dietary amino acid concentration on performance of lactating sows. J. Anim. Sci. 77:1638-1644.

Jones, D.B., and T.S. Stahly. 1999. Impact of amino acid nutrition during lactation on body nutrient mobilization and milk nutrient output in primiparous sows. J. Anim. Sci. 77:1513-1522.

Jongbloed A.W., and N.P. Lenis. 1992. Alteration of nutrition as a means to reduce environmental pollution by pigs. Livestock Prod. Sci. 31: 75-94.

Just, A. 1982. The net energy value of crude (catabolized) protein for growth in pigs. Livestock Prod. Sci. 9:349-360.

Just, A. 1984. Nutritional manipulation and interpretation of body compositional differences in growing swine. J. Anim. Sci. 58:740-752.

Kerr, B.J., and R.A. Easter. 1986. The effect of meal frequency and lysine supplementation on nitrogen retention of gravid gilts. J. Anim. Sci. 63 (Suppl 1.):272 (Abstr.).

Kerr, B.J. and R.A. Easter. 1995. Effect of feeding reduced protein, amino acid-supplemented diets on nitrogen and energy balance in grower pigs. J. Anim. Sci. 73:3000-3008.

Kerr, B.J., F.K. McKeith, and R.A. Easter. 1995. Effect on performance and carcass characteristics of nursery to finisher pigs fed reduced crude protein, amino acid-supplemented diets. J. Anim. Sci. 73:433-440.

Kertz, A.F., L.R. Prewitt, A.G. Lane, and J.R. Campbell. 1970. Effect of dietary protein intake on creatinine excretion and the creatinine-nitrogen ratio in bovine urine. J. Anim. Sci. 30:278-282.

Kim, S.W., W.L. Hurley, I.K. Han, and R.A. Easter. 1999. Changes in tissue composition associated with mammary gland growth during lactation in sows. J. Anim. Sci. 77:2510-2516.

Kim, S.W., D.H. Baker, and R.A. Easter. 2001. Dynamic ideal protein and limiting amino acids for lactating sows: The impact of amino acid mobilization. J. Anim. Sci. 79:2356-2366.

King, R. H., Elizabeth Speirs, and P. Eckerman. 1986. A note on the estimation of the chemical body composition of sows. Anim. Prod. 43:167-170.

King, R.H., and A.C. Dunkin. 1986. The effect of nutrition on the reproductive performance of first-litter sows. 4. The relative effects of energy and protein intakes during lactation on the performance of sow and their piglets. Anim. Prod. 43:319-325.

King, R.H., M.S. Toner, and H. Dove. 1989. Pattern of milk production in sows. In: Manipulating Pig Production II. (Ed. J.L. Barnett and D.P. Hennessy). Australasian Pig Sci. Assoc., Werribee, Austrailia. pp. 98.

King, R.H., C.J. Rayner, and M. Kerr. 1993a. A note on the amino acid composition of sow's milk. Anim. Prod. 57:500-502.

King, R.H., M.S. Toner, H. Dove, C.S. Atwood, and W.G. Brown. 1993b. The response of first-litter sows to dietary protein level during lactation. J. Anim. Sci. 71:2457-2463.

King, R.H., B.P. Mullan, F.R. Dunshea, and H. Dove. 1997. The influence of piglet body weight on milk production of sows. Livestock Prod. Sci. 47:169-174.

Klaver, J., G.J.M. van Kempen, P.G.B. de Lange, M.W.A. Verstegen, and H. Boer. 1981. Milk composition and daily yield of different milk components as affected by sow condition and lactation/ feeding regimen. J. Anim. Sci. 52:1091-1097.

Klobasa, F., E. Werhahn, and J.E. Butler. 1987. Composition of sow milk during lactation. J. Anim. Sci. 64:1458-1466.

Le Bellego, L., J. van Milgen, S. Dubois, and J. Noblet. 2001. Energy utilization of low-protein diets in growing pigs. J. Anim. Sci. 79:1259-1271.

Le Bellego, L., J. van Milgen, and J. Noblet. 2002. Effect of high temperature and low-protein diets on the performance of growing-finishing pigs. J. Anim. Sci. 80:691-701.

Lee, J.H., J.H. Kim, J.D. Kim, S.W. Kim, and In K. Han. 2001. Effects of low crude protein diets supplemented with synthetic amino acids on performance, nutrient utilization and carcass characteristics in finishing pigs reared using a phase feeding regimen. Asian-Aust. J. Anim. Sci. 14:655-667.

Lenis, N.P. 1989. Lower nitrogen excretion in pig husbandry by feeding: current and future possibilities. Neth. J. Agric. Sci. 37:61-70.

Lewis, A.J., and N. Nishmura.1995. Valine requirement of the finishing pig. J. Anim. Sci. 73:2315-2318.

Llames, J. and J. Fontaine. 1994. Determination of amino acids in feeds: Collaborative study. Journal of AOAC International. 77:1362-1402.

Mahan, D.C. 1977. Effect of feeding various gestation and lactation dietary protein sequences on long-term reproductive performance in swine. J. Anim. Sci. 45:1061-1072.

Mathison, G.W., J. Buchanan-Smith, S. Möhn and R.O. Ball. 1999. Feeding strategies for mitigation of greenhouse gas emissions. Consulting Report for the Agriculture and Agri-Food Round Table on Climate Change. Ottawa, Ontario.

Maynard, L.A., and J.K. Loosli. 1969. Animal Nutrition. McGraw-Hill Inc. USA.

McLean, J.A., and G. Tobin. 1987. Animal and Human Calorimetry. Cambridge University Press, New York, NY.

Mennenga, V.O. 1986. Lysine and tryptophan supplementation of low-protien, corn-soybean meal diets for lactating swine. M.Sc. Thesis. University of Illinois, Urbana Champaign, IL.

Misselbrook, T.H., D.R. Chadwick, B.F. Pain, and D.M. Headon. 1998. Dietary manipulation as a means of decreasing N losses and methane emissions and improving herbage N uptake following application of pig slurry to grassland. J. Agric. Sci. 130:183-191.

Myer, R.O., J.H. Brendemuhl, and R.D. Barnett. 1996. Crystalline lysine and threonine supplementation of soft red winter wheat or triticale, low-protein diets for growing-finishing swine. J. Anim. Sci. 74:577-583.

Noblet, J., and M. Etienne. 1986. Effect of energy level in lactating sows on yield and composition of milk and nutrient balance of piglets. J. Anim. Sci. 63:1888-1896.

Noblet, J., and M. Etienne. 1987. Metabolic utilization of energy and maintenance requirements in pregnant sows. Livestock. Prod. Sci. 16:243-257.

Noblet, J., Y. Henry, and S. Dubois. 1987. Effect of protein and lysine levels in the diet on body gain composition and energy utilization in growing pigs. J. Anim. Sci. 65:717-726.

Noblet, J. and M. Etienne. 1989. Estimation of sow milk nutrient output. J. Anim. Sci. 67:3352-3359.

Noblet, J., J.Y. Dourmad, M. Etienne and J. Le Dividich. 1997. Energy metabolism in pregnant sows and newborn pigs. J. Anim. Sci. 75:2708-2714.

Noblet, J., M. Etienne, and J.-Y. Dourmad. 1998. Energetic efficiency of milk production. In: The Lactating Sow. Chapter 6. (Eds. M.W.A. Verstegen, P.J. Moughan, and J.W. Schrama). Wageningen University Press, The Netherlands. pp. 113-130.

NRC. 1998. Nutrient Requirements of Swine (10th Ed.). National Academy Press. Washington, DC.

O'Grady, J.F., and T.J. Hanrahan. 1975. Influence of protein level and amino-acid supplementation of diets fed in lactation on the performance of sows and their litters. 1. Sow and litter performance. Ir. J. Agric. Sci. 14:127-135.

Pettigrew, J.E. 1981. Supplemental dietary fat for peripartal sows: a review. J. Anim. Sci. 53:107-117.

Pettigrew, J.E., A.F. Sower, S.G. Cornelius, and R.L. Moser. 1985. A comparison of isotope dilution and weigh-suckle-weigh methods for estimating milk intake by pigs. Can. J. Anim. Sci. 65:989-992.

Pettigrew, J.E., S.G. Cornelius, R.L. Moser, and A.F. Sower. 1987. A refinement and evaluation of the isotope dilution method for estimating milk intake by piglets. Livestock Prod. Sci. 16:163-174.

Prunier, A., C.A. Mejia Guadarrama, J. Mourot, and H. Quesnel. 2001. Influence of feed intake during pregnancy and lactation on fat body reserve mobilization, plasma leptin and reproductive function of primiparous lactating sows. Reprod. Nutr. Dev. 41:333-347.

Quiniou, N., S. Dubois, and J. Noblet. 1995. Effect of dietary crude protein level on protein and energy balances in growing pigs: comparison of two measurement methods. Livestock Prod. Sci. 41:51-61.

Renaudeau, D., and J. Noblet. 2001. Effects of exposure to high ambient temperature and dietary protein level on sow milk production and performance of piglets. J. Anim. Sci. 79: 1540-1548.

Renaudeau, D., N. Quiniou, and J. Noblet. 2001. Effects of exposure to high ambient temperature and dietary protein level on performance of multiparous sows. J. Anim. Sci. 79:1240-1249.

Revell, D.K., I.H. Williams, B.P. Mullan, J.L. Ranford, and R.J. Smits. 1998b. Body composition at farrowing and nutrition during lactation affect the performance of primiparous sows: II. Milk composition, milk yield, and pig growth. J. Anim. Sci. 76: 1738-1743.

Sauber, T.E., T.S. Stahly, N.H. Williams, and R.C. Ewan. 1998. Effect of lean growth genotype and dietary amino acid regimen on the lactational performance of sows. J. Anim. Sci. 76: 1098-1111.

Sedgwick, G.W., T.F. Fenton, and J.R. Thompson. 1991. Effect of protein precipitating agents on the recovery of plasma free amino acids. Can. J. Anim. Sci. 71:953-957.

Simmons, W.K. 1972. Urinary urea nitrogen/ creatinine ratio as an indicator of recent protein intake in field studies. Am. J. Clin. Nutr. 25:539-542.

Sinclair, A.G., J.M. Shaw, S.A. Edwards, S. Hoste, and A. McCartney. 1999. The effect of dietary protein level on milk yield and composition and piglet growth and composition of the Meishan synthetic and European White breeds of sow. Anim. Sci. 68:701-708.

Sinclair, A.G., V.C. Bland, and S.A. Edwards. 2001. The influence of gestation feeding strategy on body composition of gilts at farrowing and response to dietary protein in a modified lactation. J. Anim. Sci. 79:2397-2405.

Speer, V.C., and D.F. Cox. 1984. Estimating milk yield of sows. J. Anim. Sci. 59:1281-1285.

Spinka, M, G. Illmann, Bo Algers, and Z. Stetkova. 1997. The role of nursing frequency in milk production in domestic pigs. J. Anim. Sci. 75:1223-1228.

Sutton, A.L., K.B. Kephart, M.W.A. Verstegen, T.T. Canh, and P.J. Hobbs. 1999. Potential for reduction of odorous compounds in swine manure through diet modification. J. Anim. Sci. 77: 430-439.

Swaminathan, R., J.A. Bradley, G.H. Hill, and D.B. Morgan. 1979. The nitrogen to creatinine ration in untimed samples of urine as an index of protein catabolism after surgery. Postgrad. Med. J. 55:858-861.

Tachibana, F., and H. Ubagai. 1997. Effect of reducing crude protein and energy content in diets with amino acid supplementation on nitrogen balance, performance and carcass characteristics in pigs. Anim. Sci. Technol. 68:640-649.

Tilton, S.L., P.S. Miller, A.J. Lewis, D.E. Reese, and P.M. Ermer. 1999. Addition of fat to the diets of lactating sows: I. Effects on milk production and composition and carcass composition of the litter at weaning. J. Anim. Sci. 77:2491-2500.

Tokach, M.D., J.E. Pettigrew, B.A. Crooker, G.D. Dial, and A.F. Sower. 1992a. Quantitative influence of lysine and energy intake on yield of milk components in the primiparous sow. J. Anim. Sci. 70: 1864-1872.

Tokach, M.D., R.D. Goodband, J.L. Nelssen, J.L. Laurin, and J.A. Hansen. 1992b. The effects of an ideal protein lactation diet on sow and litter performance. J. Anim. Sci. 70 (Suppl. 1):69 (Abstr.).

Trombetta, M.F., E. Codoni, S. Mattii, and A. Falaschini. 2001. Low-protein diets for lactating sows: digestive utilisation, performance parameters and environmental impact. Pig News and Information 22:119N-124N.

Trottier, N.L., C.F. Shipley, and R.A. Easter. 1997. Plasma amino acid uptake by the mammary gland of the lactating sow. J. Anim. Sci. 75:1266-1278.

van der Peet-Schwering, C.M.C., J.W.G.M. Swinkels, and L.A. den Hartog. 1998. Nutritional strategy and reprodution. In: The Lactating Sow. Chapter 12. (Eds. M.W.A. Verstegen, P.J. Moughan, and J.W. Schrama). Wageningen University Press, The Netherlands. pp. 221-240.

van Kempen, G.J.M., C. Geerse, M.W.A. Verstegen, and J. Mesu. 1985. Effect of feeding level in milk production of sows during four weeks of lactation. Neth. J. Agric. Sci. 33:23-34.

Whittemore, C.T., and H. Yang. 1989. Physical and chemical composition of the body of breeding sows with differing subcutaneous fat depth at parturition, differing nutrition during lactation and differing litter size. Anim. Prod. 48:203-212.

Wilkinson, R., D.J.A. Cole, and D. Lewis. 1984. Amino acid nutrition of the lactating sow: limitation by indispensable amino acids. Anim. Prod. 38:263-270.

Zlatnik, F.J. 1979. Urinary nitrogen excretion as related to dietary protein in pregnant women. J. Reprod. Med. 22:128-132.

Zlatnik, F.J. 1981. Urinary urea nitrogen ratios further observations. J. Reprod. Med. 26:119-121.